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ON THE APPARENT LACK OF Be X-RAY BINARIES WITH BLACK HOLES

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ABSTRACT

In our Galaxy there are 64 Be X-ray binaries known to date. Out of these, 42 host a neutron star (NS), and for the remainder the nature of the companion is unknown. None, so far, are known to host a black hole (BH). There seems to be no apparent mechanism that would prevent formation or detection of Be stars with BHs. This disparity is referred to as a missing Be–BH X-ray binary problem. We point out that current evolutionary scenarios that lead to the formation of Be X-ray binaries predict that the ratio of binaries with NSs to the ones with BHs is rather high, $F_{\rm NStoBH} \sim 10$–50, with the more likely formation models providing the values at the high end. The ratio is a natural outcome of (1) the stellar initial mass function that produces more NSs than BHs and (2) common envelope evolution (i.e., a major mechanism involved in the formation of interacting binaries) that naturally selects progenitors of Be X-ray binaries with NSs (binaries with comparable mass components have more likely survival probabilities) over ones with BHs (which are much more likely to be common envelope mergers). A comparison of this ratio (i.e., $F_{\rm NStoBH} \sim 30$) with the number of confirmed Be–NS X-ray binaries (42) indicates that the expected number of Be–BH X-ray binaries is of the order of only ∼0–2. This is entirely consistent with the observed Galactic sample.

Key words: binaries: close – black hole physics – stars: evolution – stars: neutron

Online-only material: color figures

1. INTRODUCTION

High-mass X-ray binaries host a compact object (a neutron star or a black hole) and a massive star (Liu et al. 2000, 2005, 2006). The major subclass of high-mass X-ray binaries consists of a Be star and a compact object, and they are referred to as Be X-ray binaries (BeXRBs; e.g., Hayasaki & Okazaki 2005, 2006). The Be stars are massive, generally main sequence, stars of spectral types A0–O8 with Balmer emission lines (Zorec & Briot 1997; Negueruela 1998). The BeXRBs are found with rather wide (orbital periods in the range of ∼10–300 days) and frequently eccentric orbits, and a compact object accretes from the wind of a Be star (even massive Be stars are within their Roche lobes for these wide orbits). At present, 64 BeXRBs are known in the Galaxy, and in 42 of these, the compact object was confirmed to be a neutron star (NS) due to the presence of the X-ray pulsations (see Table 1). In the remaining cases, whenever we have information concerning the nature of the compact component, such as an X-ray spectrum, it also indicates an NS. Although one cannot exclude the possibility that a few of these systems may contain white dwarfs or black holes, it is fair to state that the majority of them contain NSs as compact components.

Other classes of XRBs are less numerous with one exception. We know of 90 X-ray bursters, all of which host NSs and 44 X-ray pulsars not associated with a Be-type companion. Thirty of these NSs are associated with a supergiant type companion and 14 with a low-mass companion. In addition, we know 57 black hole (BH) candidate systems (among them are 21 confirmed BH systems; e.g., Orosz 2003; Casares 2007; Ziolkowski 2008). However, not a single BH binary containing a Be-type component has been found so far. This disparity, 42 BeXRBs with NSs versus not a single one with a BH, indeed seems striking.

The X-ray emission from BeXRBs (with a few exceptions) is of a distinctly transient nature with rather short active phases separated by much longer quiescent intervals (a flaring behavior). There are two types of flares: Type I outbursts, which are smaller and regularly repeating, and Type II outbursts, which are larger and irregular (Negueruela & Okazaki 2001; Negueruela et al. 2001). Type I bursts are observed in systems with highly eccentric orbits. They occur close to the periastron passages of an NS. They are repeating at intervals of $\sim P_{\rm orb}$. Type II bursts may occur at any orbital phase. They are correlated with the disruption of the excretion disk around the Be star (as observed in Hα line). They repeat on timescale of the dynamical evolution of the excretion disk (∼few to few tens of years). This recurrence timescale is generally much longer than the orbital period (Negueruela et al. 2001).

BeXRBs systems are known to contain two disks: an excretion disk around the Be star and an accretion disk around the NS. Both disks are temporary: the excretion disk disperses and refills on timescales ∼a few to a few tens of years (dynamical evolution of the disk, formerly known as the "activity of a Be star" Negueruela et al. (2001), while the accretion disk disperses and refills on timescales of ∼weeks to months (this is related to the orbital motion on an eccentric orbit and, on some occasions, also to the major instabilities of the excretion disk). The accretion disk might be absent over a longer period of time (∼years) if the other disk is very weak or absent. The X-ray emission of BeXRBs is controlled by the centrifugal gate mechanism, which, in turn, is operated both by the periastron passages (Type I bursts) and by the dynamical evolution of the excretion disk (both types of bursts). This mechanism explains the transient nature of the X-ray emission (see Ziolkowski 2002 and references therein).

One should add that the excretion disks are no longer a mystery. In recent years, the outflowing viscous disks were used to describe the circumstellar matter around Be stars known

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Table 1
Galactic Be X-ray Binaries[a]

Name	P_{orb} (days)	P_{spin} (s)	e	$L_{x,max}$[b] (erg s^{-1})	Spectral Type	Ref.[c]
2S 0053+604	203.59		0.26	3.9×10^{34}	B0.5 Ve	1,2
4U 0115+634	24.3	3.61	0.34	3.0×10^{37}	B0.2 Ve	1,2
IGR J01363+6610				1.3×10^{35}	B1 Ve	1,2
RX J0146.9+6121		1404.2		3.5×10^{35}	B1 Ve	1,2
IGR J01583+6713					Be	1
1E 0236.6+6100	26.496		0.55	2.0×10^{34}	B0 Ve	1,2,3
V 0332+53	34.25	4.4	0.37	$>1.0 \times 10^{38}$	O8.5 Ve	1,2
4U J0352+309	250.3	837.0	0.11	3.0×10^{35}	O9.5 IIIe–B0 Ve	1,2
RX J0440.9+4431		202.5		3.0×10^{34}	B0.2 Ve	1,2
EXO 051910+3737.7				1.3×10^{35}	B0 IVpe	1,2
1A J0535+262	111.0	103.4	0.47	2.0×10^{37}	O9.7 IIIe	1,2,4
1H 0556+286					B5ne	1
IGR J06074+2205					B0.5 Ve	1,5
SAX J0635.2+0533	11.2	0.0338		$9 \div 35 \times 10^{33}$	B1 IIIe–B2 Ve	1,2
XTE J0658−073		160.4		6.6×10^{36}	O9.7 Ve	1,2
3A J0726−260	34.5	103.2		2.8×10^{35}	O8–9 Ve	1,2
1H 0739−529					B7 IV–Ve	1
1H 0749−600					B8 IIIe	1
RX J0812.4−3114	81.3	31.8851		1.1×10^{36}	B0.2 IVe	1,2
GS 0834−430	105.8	12.3	0.12	1.1×10^{37}	B0–2 III–Ve	1,2
GRO J1008−57	247.5	93.5	0.66	2.9×10^{35}	B0e	1,2
RX J1037.5−5647		862.0		4.5×10^{35}	B0 III–Ve	1,2
1A 1118−615		407.68		5.0×10^{36}	O9.5 Ve	1,2,6
IGR J11435−6109	52.46	161.76			Be	1,7
2S 1145−619	187.5	292.4	>0.5	7.4×10^{34}	B0.2 IIIe	1,2
1H 1253−761					B7 Vne	1
1H 1255−567					B5 Ve	1
4U 1258−61	132.5	272.0	>0.5	1.0×10^{36}	B0.7 Ve	1,2
2RXP J130159.6−635806		704.0		5.0×10^{35}	Be ?	1,2
SAX J1324.4−6200		170.84			Be ?	1
1WGA J1346.5−6255				6.6×10^{32}	B0.5 Ve	1,2
2S 1417−624	42.12	17.6	0.446	8.0×10^{36}	B1 Ve	1,2
SAX J1452.8−5949		437.4		8.7×10^{33}	Be ?	1,2
XTE J1543−568	75.56	27.12	<0.03	$>1.0 \times 10^{37}$	Be ?	1,2
2S 1553−542	30.6	9.26	<0.03	7.0×10^{36}	Be ?	1,2
IGR J15539−6142				3.3×10^{33}	B2–3 Vne	1,2
IGR J16207−5129				1.3×10^{34}	B8 IIIe	1,2
SWIFT J1626.6−5156		15.37			Be	2
AX J170006−4157		714.5		7.2×10^{34}	Be ?	1,2,8
RX J1739.4−2942					Be ?	1
RX J1744.7−2713				1.8×10^{32}	B0.5 V–IIIe	1,2
AX J1749.2−2725		220.38		2.6×10^{35}	Be ?	1,2
GRO J1750−27	29.8	4.45			Be ?	1
1XMM J180816.8−191940				1.3×10^{33}	Be ?	2
AX J1820.5−1434		152.26		9.0×10^{34}	O9.5–B0 Ve	1,2
XTE J1824−141		120.0			Be ?	9
1XMM J183327.7−103523				$1.6 \div 7.5 \times 10^{32}$	B0.5 Ve	2
1XMM J183328.7−102409				3.3×10^{32}	B1–1.5 IIIe	2
GS J1843+00		29.5		3.0×10^{37}	B0–2 IV–Ve	1,2
2S 1845−024	242.18	94.8	0.88	6.0×10^{36}	Be ?	1,2
XTE J1858+034		221.0			Be ?	1
4U 1901+03	22.58	2.763	0.036	1.1×10^{38}	Be ?	1,2
XTE J1906+09	28.0 ?	89.17			Be ?	1
1H 1936+541					Be	1
XTE J1946+274	169.2	15.8	0.33	5.4×10^{36}	B0–1 IV–Ve	1,2
KS 1947+300	40.415	18.76	0.03	2.1×10^{37}	B0 Ve	1,2
W63 X-1		36.0			Be ?	1
EXO 2030+375	46.02	41.8	0.41	1.0×10^{38}	B0 Ve	1,2
RX J2030.5+4751				1.7×10^{33}	B0.5 V–IIIe	1,2
GRO J2058+42	55.03	198.0		2.0×10^{36}	O9.5–B0 IV–Ve	1,2
SAX J2103.5+4545	12.68	358.61	~ 0.4	3.0×10^{36}	B0 Ve	1,2
1H 2138+579		66.33		9.1×10^{35}	B0–2 IV–Ve	1,2,10
1H 2202+501					Be	1

Table 1
(Continued)

Name	P_{orb} (days)	P_{spin} (s)	e	$L_{x,max}$[b] (erg s^{-1})	Spectral Type	Ref.[c]
SAX J2239.3+6116	262.6	1247.0		$\sim 2.3 \times 10^{36}$	B0 V–B2 IIIe	1,2

Notes.
[a] Note that we have not included the following systems: 1H 1249−637 (compact companion is probably a white dwarf, Liu et al. 2006); IGR J16318−4848 (optical component is B[e] with strong supergiant wind and not a typical Be star; Liu et al. 2006); 1H 1555−552 (Herbig Ae/Be optical component, Liu et al. 2006); PSR B1259 (non-accreting XRB, Tavani & Arons 1997).
[b] Maximum X-ray luminosity.
[c] (1) Liu et al. 2006; (2) Raguzova 2007; (3) Grundstrom et al. 2007; (4) Smith et al. 2005; (5) Reig & Zezas 2009 (6) Mangano 2009; (7) Tomsick et al. 2007; (8) Torii et al. 1999; (9) Markwardt et al. 2008; (10) Beklen & Finger 2009.

earlier as "an envelope of a Be star" (Okazaki 1997; Porter 1999; Negueruela & Okazaki 2001). The modeling with the help of the viscous excretion disks appeared to be by far more successful in describing the circumstellar matter than earlier descriptions in terms of "equatorial winds," "expanding envelopes," or "ejected shells." In particular, the viscous excretion disk models were able to explain the very low outflow velocities (the observed upper limits are, at most, a few km s^{-1}) and also to explain the (so-called) V/R variability observed in Be stars. The viscous excretion disks are very similar to the well-known viscous accretion disks, except for the changed sign of the rate of the mass flow. Some aspects of the modeling (e.g., the supply of matter with the sufficient angular momentum to the inner edge of the disk, the interaction of the stellar radiation with the disk matter) are not fully solved yet, but the general picture is quite convincing. The viscosity in the excretion disks (and similarly, for accretion disks) is usually assumed to be in the form of α-viscosity. The disks are almost Keplerian (rotationally supported), which explains the very low values of the radial component of velocity. Nearly Keplerian disks (both inflowing and outflowing) have, long been known to undergo a global one-armed oscillation instability (Kato 1983). This instability (progressing density waves) provides a very successful explanation of V/R variability observed both in isolated Be stars and in members of Be/X-ray systems. This phenomenon manifests itself in the form of quasi-cyclical changes of the ratio of the strengths of the V (violet) peak to the R (red) peak in the double profile emission lines. This variability (best seen in the Hα line) includes phases when only one peak is visible. The timescales of the quasi-cycles range from months to years or decades. The theoretical line profiles calculated for the disks with an asymmetric matter distribution due to progressing density waves were found to be in good agreement with the observed profiles (Okazaki 1996; Hummel & Hanuschik 1997). Also the theoretical timescales calculated for the one-armed oscillation instability agreed with the observed timescales of V/R variability (Negueruela et al. 2001). The one-armed instability ultimately leads to the disruption of the disk and ejection of the matter from its outer rim. This phenomenon is believed to be responsible for Type II bursts. Therefore, these timescales also describe the recurrence of Type II bursts.

The total number of BeXRBs in the Galaxy is difficult to estimate. The typical duty cycle (the relative length of the interval of the high X-ray emission, during which the system might be detected) is rather small: ∼1% to ∼10% (with the exception of a few persistent sources). The coverage of the sky by X-ray surveys is very far from complete. Many systems lie in the obscure regions of the Galaxy, and they might be detected only in hard X-rays. With the exception of *INTEGRAL*, which has hard X-ray capability that has led to the discovery of many new BeXRBs, (Bird et al. 2007), these systems are undetectable by most X-ray observatories. Since most of the BeXRBs are dormant at any given moment, we can expect to discover many new such systems in the near future. It might be estimated that the total number of BeXRBs in the Galaxy is perhaps an order or two orders of magnitude larger than the number of presently known systems (e.g., Rappaport & van den Heuvel 1982; van den Heuvel & Rappaport 1987).

In a series of conference proceeding papers (Sadowski et al. 2008a, 2008b, 2008c), we have reported a potential solution to the problem of the missing BH BeXRBs. This solution was incorrect and we want to stress that these papers should not be used. The errors were made in population synthesis result analysis. In the present study, we have performed the calculations anew and we have double checked our analysis. Additionally, all the calculations were performed with the revised code (see Section 2.1). The new results along with the new and qualitatively different solution to the missing problem are presented here.

In this work, we study the origins of the apparent disparity between the number of known BeXRBs with NSs (42) and the number of known BeXRBs with BHs in the Galaxy. This disparity has been noted in the literature for some time. The first stellar population synthesis calculations intended to estimate the number of BH BeXRBs were carried out by Raguzova & Lipunov (1999). They *assumed* that the ratio of BeXRBs with an NS to the ones with a BH is ∼25. This was based on 25 Galactic NS BeXRBs known at that time and the assumption that GRS 1915+105 is a BH Be X-ray binary. We know now that this is not the case and that GRS 1915+105 is a low-mass X-ray binary with the donor star that is a low-mass (K–M) giant (e.g., Greiner et al. 2001). They demonstrated that by adjusting some evolutionary parameters (e.g., natal kicks, the initial star mass that divides an NS from a BH formation) their model can reproduce the ratio of ∼25. However, some of their adjustments seem to be rather extreme in light of the current understanding of binary evolution. For example, they needed to assume that stars form black holes *only* if their mass is higher than $\sim 60\, M_\odot$ and that *each* main sequence star above $10\, M_\odot$ becomes a Be star after a mass accretion episode. Another population synthesis study connected to the Be phenomenon was presented by Zhang et al. (2004). In this study, it was noted that according to the stellar population synthesis calculations by Podsiadlowski et al. (2003), BH binaries are predominantly formed with relatively short orbital periods ($P_{orb} < 10$ days). If this is the case, then, according to Zhang et al. (2004), the excretion disk truncation mechanism (Artymowicz & Lubow 1994) might be so efficient that the accretion rate is very low and the system remains dormant (and therefore invisible) almost all the time. One should note, however, that Podsiadlowski et al. (2003) essentially considered BH systems with Roche lobe filling secondaries, which is definitely not the case for BeXRBs (wind-fed accretion; e.g., Negueruela 1998; Ziolkowski 2002).

We want to stress that in this paper we consider only Galactic BeXRBs. However, it should be added that there exists a large population of BeXRBs in the Magellanic Clouds (e.g., Liu et al. 2005). It is even larger than that of the Galaxy: 74 known systems with 47 containing a confirmed pulsar; J. Ziolkowski 2009, unpublished compilation. Moreover, this population is growing very fast. Taking into account that the total stellar content of the Magellanic Clouds is much smaller than the Galactic one, the study of the origin of this population might be very interesting. Due to very different properties of stellar populations (e.g., lower metallicity, different star formation history), we defer the study of BeXRBs in the Magellanic Clouds to another paper.

2. MODEL

2.1. Population Synthesis

Binary population synthesis is used to calculate the population of massive stars (spectral types B/O) that are in binaries with a compact object, either an NS or a BH. The population synthesis code employed in this work, `StarTrack`, was initially developed for the study of double compact object mergers in the context of gamma-ray burst (GRB) progenitors (Belczynski et al. 2002a) and gravitational-wave inspiral sources (Belczynski et al. 2002b). Single stellar evolution is based mostly on the modified set of stellar models of Hurley et al. (2000), while binary evolution procedures were independently developed for this code.

In recent years, `StarTrack` has undergone major updates and revisions in the physical treatment of various binary evolution phases, especially in mass transfer phases. The new version has already been tested and calibrated against observations and detailed binary mass transfer calculations (Belczynski et al. 2008) and has been used in various applications. The physics updates that are most important for compact object formation and evolution include: (1) a full numerical approach to orbital evolution due to tidal interactions, calibrated using high-mass X-ray binaries and open cluster observations; (2) a detailed treatment of mass transfer episodes fully calibrated against detailed calculations with a stellar evolution code; (3) updated stellar winds for massive stars (see Belczynski et al. 2009a); and (4) the latest determination of the natal kick velocity distribution for NSs (Hobbs et al. 2005). For He star evolution, which is of crucial importance for the formation of double NS binaries (e.g., Ivanova et al. 2003; Dewi & Pols 2003), we have applied a treatment closely matching the results of detailed evolutionary calculations. If the He star expands and Roche lobe overflow (RLOF) begins, the systems are examined for the potential development of a dynamical instability, in which case they are evolved through a common envelope (CE) phase. Otherwise a highly non-conservative mass transfer ensues. We treat CE events using energy formalism (Webbink 1984), where the binding energy of the envelope is determined from the set of He star models calculated with the detailed evolutionary code by Ivanova et al. (2003). The progenitor evolution and RLOF episodes are now followed in much greater detail. In particular, the code was calibrated for various cases of mass transfer in massive binaries and then tested against some published detailed evolutionary tracks (e.g., Wellstein et al. 2001).

One specific evolutionary process that plays an important role for the formation of binaries with BHs is the CE phase. This phase is instrumental in decreasing orbital separation and bringing initially distant binary components close to each other. This in turn allows components of many systems to begin an interaction and manifest their presence through a number of observational phenomena. The inspiral process in CE and the subsequent decrease of an orbit is not well understood. It is believed that only donor stars (initiating the process) with well developed core-envelope structures like red giants can successfully survive the inspiral. On the other hand, stars with no clear core–envelope boundary, like main-sequence stars, cannot survive this phase, leading to a CE merger and the formation of one rapidly rotating and peculiar star.

It was pointed out that stars crossing the Hertzsprung gap (HG) do not have a clear entropy jump at the core–envelope transition (Ivanova & Taam 2004). Therefore, it can be expected that if such a star overflows its Roche lobe and initiates a CE phase the inspiral will eventually lead to a merger (e.g., Taam & Sandquist 2000). This possibility was tested in evolutionary calculations of merger rates of double compact objects. It turns out that if such a possibility is accounted for, the merger rates of BH–BH binaries decrease drastically (by a factor of $\sim$500). NS–NS merger rates drop only moderately (Belczynski et al. 2007). Since the details of the CE phase are not fully understood, in this study we will also test this possibility in our predictions for BeXRBs. In model A, we will allow for survival even if a donor star is on the HG (i.e., standard energy balance is calculated to check on the outcome of CE), while in model B, any CE phase that involves an HG donor is *assumed* to lead to a merger aborting subsequent binary evolution and potential formation of a BeXRB.

Another important factor that determines the formation efficiencies of binaries with NSs and BHs is the natal kick compact objects receive at birth. For models A and B, we adopt natal kicks from the radio pulsar birth velocity distribution derived by Hobbs et al. (2005; a Maxwellian distribution with $\sigma = 265$ km s^{-1}) for NSs that are formed in regular core-collapse supernovae, while for NSs formed in electron capture supernovae, we adopt no natal kicks (e.g., Dessart et al. 2006). Natal kicks for black holes are decreased proportionally to the amount of fallback expected during core collapse/supernova explosion (e.g., Fryer 1999; Fryer & Kalogera 2001). However, we calculate one extra model in which natal kicks are reduced. In particular, in model C, NS kicks are drawn from a Maxwellian distribution with $\sigma = 133$ km s^{-1}, while BH kicks are derived from the same distribution but then decreased due to the fallback. For the electron capture NS formation, no natal kicks are applied. There are some indications that the natal kicks NSs receive are smaller for stars in binaries as compared with single stars (e.g., Podsiadlowski et al. 2004). Here we have decreased the value of kicks as measured by Hobbs et al. (2005) for single pulsars by half and applied them to neutron stars in binaries. This specific choice was motivated by the recent calculation that demonstrated that in order to reproduce the ratio of recycled pulsars in double neutron star binaries (nine known) to single-recycled pulsars (four) the kicks operating in binary stars are required to be rather low ($\sigma \lesssim 133$ km s^{-1}; Belczynski et al. 2009b).

Delineation in the formation of NSs and BHs may play an important role in the expected number of BeXRBs with different accretors. In particular, we still do not know what a star in the initial mass range of $M_{\rm zams} = 20$–$40\,M_\odot$ forms: a neutron star or a black hole? In this study, we have employed a physical model for the formation of a compact object, and rather than using a star initial mass (as most population synthesis codes do), we have used the star properties to delineate the formation of a neutron star from the formation of a black hole. In short, we follow the evolution of a given star, note the final mass of its FeNi core, and then use the results of hydro core-collapse simulations to estimate the mass of the compact object a given star forms. Once we have the mass of a compact object we use the maximum neutron star mass (assumed to be $2.5\,M_\odot$) to tell apart neutron stars from black holes. The full description of this scheme is given in Belczynski et al. (2008 and references therein). As it happens, our scheme (for single stars) results in the black hole formation for $M_{\rm zams} \gtrsim 20\,M_\odot$ (see Belczynski et al. 2009b). If we wanted to (artificially) adopt a higher limit (e.g., $M_{\rm zams} \gtrsim 40\,M_\odot$), we would expect more BeXRBs with neutron stars than predicted in the following sections. In other words, our conclusions are rather conservative on the estimate of the ratio of BeXRBs with NSs to the ones with BHs. If anything such a ratio should be higher and our conclusions that follow stronger.

2.2. Calculations

We evolve a Galactic population of massive binaries using `StarTrack`. We adopt solar metallicity $Z = 0.02$ and a steep initial mass function (IMF) for massive stars with a power-law exponent of -2.7 (Kroupa et al. 1993; Kroupa & Weidner 2003). RLOF is treated in a non-conservative way (with 50% mass loss from a given binary; e.g., Meurs & van den Heuvel 1989) while the CE phase is treated via energy balance with fully efficient transfer of orbital energy into dispersal of an envelope (e.g., $\alpha \times \lambda = 1.0$). The results are calibrated in such a way that the Galactic star formation rate is at the level of $3.5\,M_\odot\,{\rm yr}^{-1}$ and is constant through the last 10 Gyr (e.g., O'Shaughnessy et al. 2006). At the present Galactic disk age ($t = 10$ Gyr) we perform a time slice and extract BeXRBs using the classification criteria defined in the following section.

2.3. Be X-ray Binary

Following the earlier discussion (Section 1) of the observed properties of the Galactic population of BeXRBs, we adopt a definition (that is extended to potential systems that may host a BH) of a BeXRB in our population synthesis calculations. We call any system a BeXRB if: (1) it hosts either an NS or a BH accretor; (2) the donor is a main sequence star (i.e., burning H in its core); (3) the donor mass is high, $M_{\rm don} \geqslant 3.0\,M_\odot$ (O/B star); (4) accretion proceeds *only* via stellar wind (no RLOF); (5) its orbital period is in the range 10 days $\leqslant P_{\rm orb} \leqslant 300$ days; and (6) only a fraction $F_{\rm Be} = 0.25$ of the above systems are designated as hosting a Be star and not a regular O/B star. The observations indicate that the fraction of Be stars among all B stars is 1/5–1/3 (e.g., Slettebak 1988; Ziolkowski 2002; McSwain & Gies 2005). Note that in the above definition we do not require a non-zero eccentricity, as for the Galactic BeXRBs as many as ~20% of systems have small eccentricity ($\lesssim 0.1$).

We have chosen to define BeXRB in a phenomenological way, and we have adopted the values for our limiting factors based on the observational properties (e.g., $F_{\rm Be}$). Note also that we have not put any constraints on the spin of a Be star. As Be stars are known to have high rotational velocities, it translates into an assumption (e.g., Slettebak 1949, 1966; Slettebak et al. 1992) that either some stars are born with initially high spins or that the mass accretion during RLOF can effectively spin up a massive star. The more physical approach (e.g., B star becomes Be star if spun up via RLOF accretion) is also potentially possible within the framework of our population synthesis model. However, the details of such a model would be highly uncertain (e.g., the high spin of Be stars may be connected to their initial rapid rotation and not to RLOF spin up; it is not certain if any spin up is expected during CE phase, and how effectively angular momentum can be transferred during RLOF). We note that the adopted value of $F_{\rm Be}$ affects only the absolute number of BeXRBs predicted in our calculations. However, the physical properties or the relative ratio of BeXRBs hosting an NS to the ones hosting a BH remains the same and therefore our results and conclusions (see below) are independent of the value we adopt for $F_{\rm Be}$.

Table 2
Simulations: Be X-ray Binary Formation Channels

Formation Channel	Efficiency (%)[a] Model A	(B)	[C]	Evolutionary History[b]
BeNS:01	44.2	(41.8)	[45.3]	CE:a→b, SN:a
BeNS:02	42.3	(43.9)	[45.0]	CE:a→b, NC:a→b, SN:a
BeNS:03	11.9	(13.3)	[8.8]	NC:a→b, SN:a
BeNS:04	1.6	(1.0)	[0.9]	All other
BeBH:01	79.6	(13.2)	[17.2]	CE:a→b, SN:a
BeBH:02	19.8	(85.5)	[82.8]	NC:a→b, SN:a
BeBH:03	0.6	(1.3)	[0.0]	All other
$N_{\rm BeNS}$	579	(517)	[1578]	Galactic number of NS BeXRBs
$N_{\rm BeBH}$	82	(19)	[29]	Galactic number of BH BeXRBs
$F_{\rm NStoBH}$	7	(27)	[54]	Number ratio of NS to BH BeXRBs

Notes.
[a] Efficiency for models with standard kicks ($\sigma = 265$ km s^{-1}) in which survival through a CE phase with an HG donor is allowed (A) and not allowed (B). Model C shows results for evolution with small kicks ($\sigma = 133$ km s^{-1}) and the survival in CE with HG donors is not allowed.
[b] Sequences of different evolutionary phases for the primary (a) and the secondary (b): non-conservative mass transfer, NC; common envelope, CE; and supernova explosion/core collapse event (SN). Arrows mark direction of mass transfer episodes.

3. RESULTS

3.1. Models A and B

In Table 2, the main results of our calculations are presented. The main formation channels for BeXRBs are given separately for systems with NSs (marked BeNS:0N, where N is a number that indicates a given channel) and BHs BeBH:0N). We also list the predicted intrinsic Galactic number of BeXRBs ($N_{\rm BeNS}$, $N_{\rm BeBH}$), along with the expected ratio of systems with NSs to systems with BHs ($F_{\rm NStoBH}$).

Binaries with NSs form mostly along two channels. One (BeNS:01 forms ~45% of BeXRBs with NSs) involves a CE phase when the primary is an evolved star (e.g., burning He in its core, or burning H and He in a shell) and after losing the envelope, the combination of the post-CE orbital separation (rather large) and maximum radius of exposed primary core (not too large) is such that there are no more interactions until the primary's exposed core explodes and forms an NS. The other channel (BeNS:02, ~45%) also involves the initial CE phase,

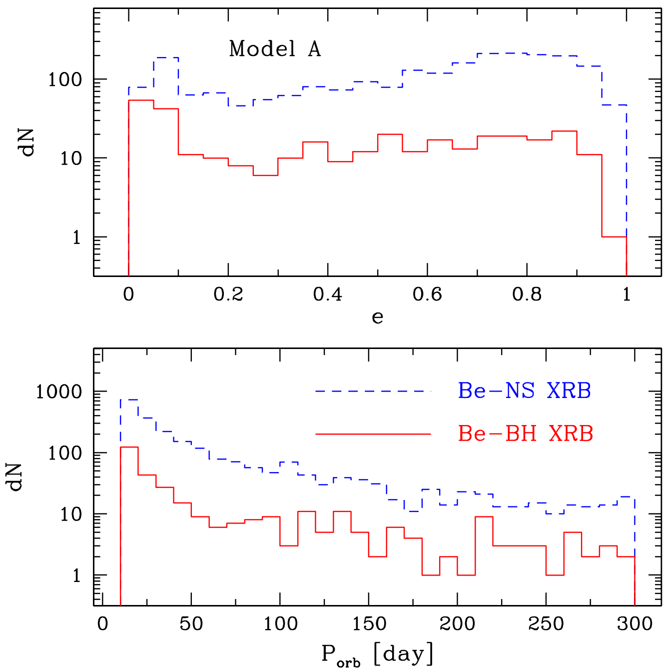

Figure 1. Orbital period and eccentricity distributions for different populations of Be X-ray binaries. Systems with neutron stars are more abundant than ones with BH accretors. However, the distribution of periods is rather similar for both populations. Distributions correspond to model A in which survival through a CE phase with an HG donor is allowed (for details see Section 2.1). Note that for the sake of presentation, we show the entire population (i.e., $F_{\rm Be} = 1.0$) of potential BeXRBs, and the actual synthetic Galactic population as presented in Table 2 was obtained by drawing only 1/4 of systems from these distributions (i.e., $F_{\rm Be} = 0.25$).

(A color version of this figure is available in the online journal.)

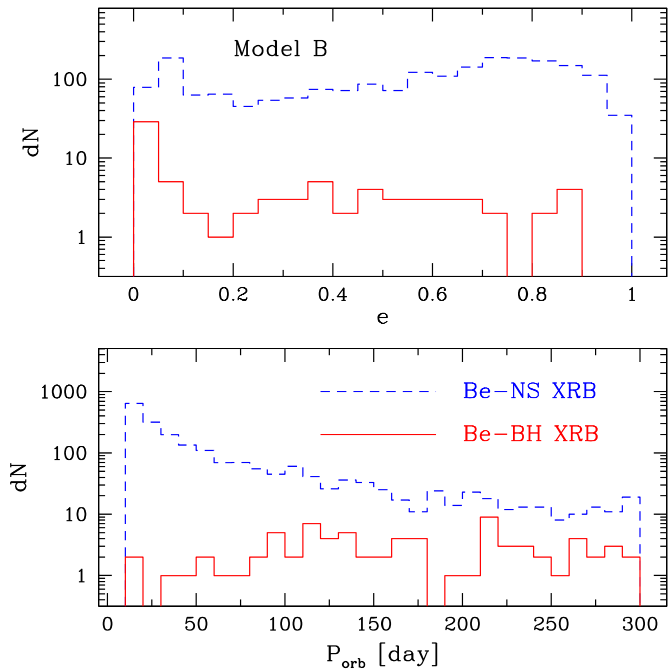

Figure 2. Same as Figure 1 but for model B in which survival through a CE phase with an HG donor is not allowed. Note the significantly smaller number of Be-BH X-ray binaries, and the moderately smaller number of Be-NS X-ray binaries.

(A color version of this figure is available in the online journal.)

but it usually starts on a smaller orbit so the post-CE separation is such that it allows the exposed core of the primary (naked He star) to overflow its Roche lobe and start another interaction (non-conservative mass transfer) before it explodes and forms an NS. There is also one channel (BeNS:03, ∼10%) that involves two binary components of comparable mass, and once RLOF begins, it does not develop into a CE phase but proceeds via a regular and not too violent way (on a thermal and/or nuclear timescale of the donor). After the RLOF episode, the primary explodes and forms an NS. At the time of NS formation, the companion is a still unevolved (main sequence) star with high mass ($M_{\rm b} \geqslant 3.0\,M_\odot$). There is not much difference from model A to model B in the formation of BeXRBs with NSs.

The formation of BeXRBs with BHs proceeds along two channels. The first one (BeBH:01) is very similar to BeNS:01 and involves a CE phase followed by the explosion of a primary and the formation of a BH. The main difference comes from the fact that in this case the primary is more massive than a progenitor of an NS in BeNS:01 and it starts a CE phase earlier in its evolution. The CE phase is encountered very often when a primary is crossing the HG as it is the first evolutionary phase at which the stars undergo a very significant radial expansion. Since we impose non-survival in such a case for model B, we note the significant decrease of BeXRBs formation in this channel from model A (∼80%) to model B (∼10%). The second formation channel of BeXRBs with BHs (BeBH:02) is almost the same as the channel BeNS:03 for binaries with NSs. Since this channel involves only one non-conservative RLOF, the change from model A (∼20%) to model B (∼90%) is only relative. This change simply reflects the decrease of the number of binaries in channel BeBH:01, and the actual number of binaries in the channel BeBH:02 does not change from model A to model B.

We also present the predicted numbers of BeXRBs calibrated for the Galactic disk star formation rate. We have randomly selected only 25% ($F_{\rm Be} = 0.25$) of the massive binaries hosting a B/O star with a compact object companion as this seems to be the fraction of Be stars among regular B stars and we have additionally imposed some constraints on orbital period and system configuration (see Section 2.3). The number of predicted BeXRBs with NSs is $N_{\rm BeNS} \sim 500$ and does not depend much on the adopted model of CE evolution. The number of BeXRBs with BHs is significantly smaller and is sensitive to the adopted CE model; we find $N_{\rm BeBH} \sim 80$ and ∼20 systems for model A and model B, respectively. This is qualitatively the same trend as found by Belczynski et al. (2007), who demonstrated that CE survival/non-survival affects mostly systems with BHs.

In each model, we predict more BeXRBs with NSs than with BHs. In general there are more NSs than BHs (∼8:2; the ratio depends on adopted IMF and the details of the transition from NS to BH formation). Additionally, binaries with initially comparable mass components (like progenitors of BeXRBs with NSs) are more likely to survive the first interaction (usually the CE phase) than the binaries with components of very different masses (like for many progenitors of BeXRBs with BHs). The number of BeXRBs with NSs is about the same in both models, but the number of binaries with BHs decreases significantly from model A to model B. Therefore, the ratio of BeXRBs with NSs to the ones with BHs changes significantly from model A ($F_{\rm NStoBH} = 7$) to model B ($F_{\rm NStoBH} = 27$).

In Figures 1 and 2, we present the distributions of orbital periods and eccentricities for the synthetic BeXRBs for models A and B. Due to the small number of binaries predicted in the Galaxy, the distributions are constructed from the entire population of potential BeXRBs (i.e., $F_{\rm Be} = 1.0$). The actual

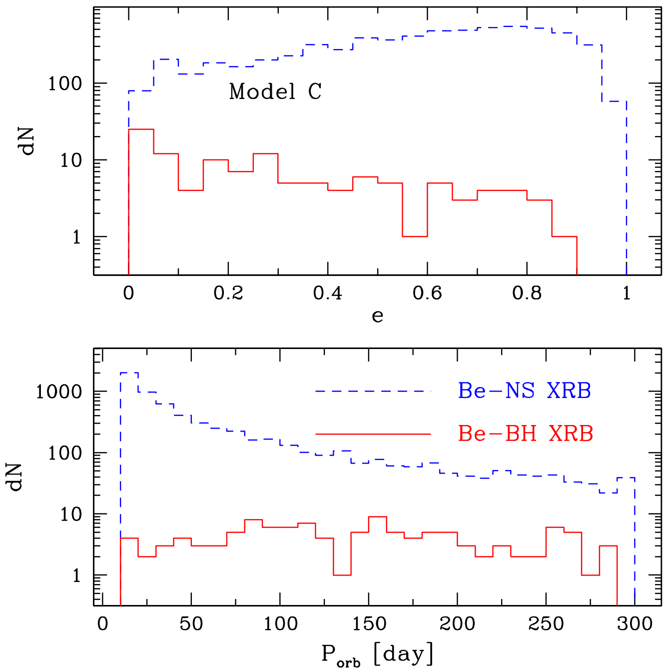

Figure 3. Same as Figure 1 but for model C in which natal kicks are decreased by half as compared to models A and B. In this model, the survival through a CE phase with an HG donor is not allowed. Note the significantly larger number of Be-NS X-ray binaries, and the moderately larger number of Be-NS X-ray binaries.

(A color version of this figure is available in the online journal.)

population of synthetic Galactic Be X-ray binaries as listed in Table 2 (i.e., $F_{\rm Be} = 0.25$) is constructed by random drawing from the distributions shown in Figures 1 and 2.

Orbital periods are contained within 10 days $\leqslant P_{\rm orb} \leqslant$ 300 days by our adopted definition of BeXRBs (see Section 2.3). The distributions within these limits are falling off with increasing periods and this general trend holds for both BeXRBs with NSs and BHs. The relatively large number of systems with small periods is the outcome of the orbital contraction during the CE phase. This is indirectly, but very clearly, demonstrated by the example of BeXRBs with BHs in model B (Figure 2) in which majority of the systems do not evolve through a CE phase, and there are almost no binaries with small periods (i.e., $P_{\rm orb} \leqslant 50$ days).

The eccentricity distributions are similar for models A and B. For BeXRBs with NSs there is an overall trend of distributions with rising eccentricity. This is an effect of natal kicks that are rather high ($\sigma = 265$ km s^{-1}) so binaries in general receive high kicks and gain significant eccentricity after the first supernova. It is noted that we plot here only the tail of the entire population of initial binaries that may have become BeXRBs but were disrupted in the first supernova. Actually, the disruption at the first supernova for massive binaries is very high ($\gtrsim$95%) and only very few binaries survive. There is also an accumulation of systems with very small eccentricities ($e \lesssim 0.1$) and this is due to the population of neutron stars that form through electron capture supernovae for which we have assumed no natal kicks, so the small but non-zero eccentricities for these systems arise from mass loss only.

The general trends are very similar for distributions of eccentricities for BeXRBs with BHs. However, we note two natural changes in the relative strengths of the distribution trends of binaries with BHs compared to the distributions of binaries with NSs. First, the increase of distribution with eccentricity is smaller for binaries with BHs as these receive, on average, lower natal kicks than NSs due to the fallback and smaller explosion energies in BH formation. Second, the contribution of BH binaries with small eccentricities is higher than for binaries with NSs. The most massive BHs form through direct collapse (or almost full fallback) for which we assume no (or rather small) natal kicks and since there is no (or almost no) mass loss, these systems end up with zero (or very small) eccentricities.

3.2. *Model C*

In model C, we have decreased the natal kicks that NSs and BHs receive, and this model is similar to model B since in this calculation, we do not allow for CE survival if a donor is an HG star. The formation channels and corresponding efficiencies are about the same as for model B. However, as intuitively expected, the formation of binaries with NSs increases ($N_{\rm BeNS} \sim 1500$) significantly as compared to other models (see Table 2). Since most progenitors of BeXRBs are disrupted during the formation of a compact object (via a supernova natal kick) once the kicks are decreased the formation is more efficient. The same effect is found for BeXRBs with BHs ($N_{\rm BeNS} \sim 30$) although to a lesser degree as BH kicks are assumed to be smaller and, therefore, the disruptions are not as important a factor as for binaries with NSs. This trend significantly increases the number of BeXRBs with NSs and only moderately increases the number of binaries with BHs. It therefore has a deep impact on the expected ratio of one population to the other. In particular, the ratio of BeXRBs with NSs to ones with BHs is found to be very high for model C: $F_{\rm NStoBH} = 54$. In Figure 3 we show period and eccentricity distributions for model C.

4. CONCLUSIONS

We have performed a population synthesis study of Galactic BeXRBs. In particular, we have attempted to explain the problem of the missing BeXRBs with BHs. The only known BeXRBs with a confirmed type of compact object host NSs. Specifically, we know 64 BeXRBs in the Galaxy, but only 42 of these systems are known to host an NS. None of the observed BeXRBs hosts a BH.

Our main results may be described as follows.

1. Previously, we have reported (Sadowski et al. 2008a, 2008b, 2008c) the potential solution to the problem of the missing BeXRBs. This solution was incorrect, and the mistake was due to some errors in the population synthesis data analysis. The new results (double-checked and obtained with the updated code) are presented.
2. We predict that both populations of BeXRBs should exist in the Galaxy: those with NSs as well as those with BHs.
3. The predicted number of BeXRBs with NSs is much higher (factors of $F_{\rm NStoBH} \sim 10$–50) than those with BHs.
4. If we use the preferred evolutionary models ($F_{\rm NStoBH} \sim$ 30–50; models B and C), we predict that in the observed sample of BeXRBs of 42 systems with NSs, one should expect only $\sim$0–2 systems with BHs. It is quite possible that none are yet observed (small statistics).
5. Due to the very low number of expected binaries with BHs, it is very likely that there is no problem with missing BeXRBs with BHs in the Galaxy.

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