Population Synthesis of Black Hole Binaries with Normal-star Companions. I. Detached Systems

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Abstract

Optical observations of normal stars in binary systems with massive unseen objects have been proposed to search for candidate black holes (BHs) and provide a direct measurement of their dynamical masses. In this paper, we have performed binary population synthesis calculations to simulate the potential population of detached binaries containing BHs and normal-star companions in the Galaxy. We focus on the influence of the BH progenitors. In the traditional model, BHs in binaries evolve from stars more massive than \( \sim 75 M_\odot \). However, it is difficult for this model to produce BH low-mass X-ray binaries. Recent investigations of massive star evolution have suggested that the BH progenitors have masses as low as \( \sim 15 M_\odot \). Based on this model, we provide the expected distributions of various parameters for detached BH binaries with normal-star companions, including the component masses, the orbital parameters of the binary systems, the radial velocity semi-amplitudes, and the astrometric signatures of the optical companions. Our calculations show that there are thousands of such detached binaries in the Galaxy, and hundreds of them are potentially observable systems with luminous companions brighter than 20 mag. In addition, detached BH binaries are dominated by those with main-sequence companions and only a small percent of them are expected to have giant companions.

Unified Astronomy Thesaurus concepts: Binary stars (154); Black holes (162); Stellar evolution (1599)

1. Introduction

It is believed that there are hundreds of millions of stellar-mass black holes (BHs) in the Galaxy (van den Heuvel 1992; Brown & Bethe 1994; Timmes et al. 1996). More than 40 years have passed since the discovery of the first BH in Cygnus X-1 (Bolton 1972; Webster & Murdin 1972). To date, however, only two dozen BHs have been dynamically confirmed. The majority of them are discovered in X-ray binaries (Remillard & McClintock 2006; Casares & Jonker 2014), in which the BH is accreting material from its companion star and emitting X-ray radiation. According to binary evolution theories, quite a number of binary systems are likely to host a quiescent BH orbiting its normal-star companion, prior to the X-ray binary phase, as the X-ray radiation due to BH accretion is too weak to be detected.

For decades, a promising approach based on radial velocity searches has been proposed to discover BHs in binary systems (Guseinov & Zel’dovich 1966; Trimble & Thorne 1969). Until recently, dynamical searches of optical companions were broadly used to identify BHs in binary systems. In the globular cluster NGC 3201, Giesers et al. (2018) found a main-sequence (MS) turnoff star orbiting an unseen component with large radial velocity variations. A deep analysis of the orbital parameters indicated that the unseen object is a potential BH with a minimum mass of \( \geq 4 M_\odot \). Based on spectroscopic and photometric studies of the binary AS 386, Khokhlov et al. (2018) revealed that the binary system has a circular orbit with a period of \( \sim 131 \) days, and contains a B-type star of mass 7 ± 1\( M_\odot \). Based on the absence of any traces of the secondary component, whose mass is larger than 7\( M_\odot \), Khokhlov et al. (2018) suggested that it is most likely a BH. By combining radial velocity measurement with photometric variability data, Thompson et al. (2019) discovered a candidate BH orbiting a \( \sim 3 M_\odot \) giant star with an orbital period of \( \sim 83 \) days. Because BHs discovered in such detached binaries are not subject to the effects of possible mass accretion, a large sample could provide details about the BH-mass function and test theories of binary evolution and the supernova (SN) mechanism.

According to some related surveys, the prospect of searching for BHs in binaries with visible normal stars has already been explored. Using the astrometric satellite Gaia, several groups (Breivik et al. 2017; Mashian & Loeb 2017; Yalinewich et al. 2018; Yamaguchi et al. 2018) predicted that dozens or thousands of binaries with a BH component could exist. Using the photometric data of the Transiting Exoplanet Survey Satellite, Masuda & Hotokezaka (2019) discussed the potential of identifying BHs with normal-star companions on tight but detached orbits. Based on spectroscopic observations of the Large sky Area Multi-Object fiber Spectroscopic Telescope, Gu et al. (2019) proposed a method to search for stellar-mass BH candidates in binaries with giant companions.

Stellar evolution predicts that BHs originate from massive stars with masses \( \geq 20\sim 25 M_\odot \) (Woosley & Weaver 1995; Fryer et al. 2012). The standard formation scenario for BH binaries with an initially low-mass companion usually involves a common envelope (CE) phase (see a review by Ivanova et al. 2013) in which the spiral-in of the low-mass secondary causes the ejection of the envelope of the primary (BH’s progenitor). However, it was pointed out that the primary’s envelope is too massive for a low-mass secondary to strip off (Podsiadlowski et al. 2003), probably resulting in the binary merge. In view of the CE phase, compact BH binaries with low-mass companions can be formed only if adopting high values for the binding energy parameter of the primary envelope (Podsiadlowski et al. 2003) or for the CE ejection efficiency (Kiel & Hurley 2006; Yungelson & Lasota 2008). Another solution to this problem is...
adopting relatively small masses for the BH progenitors (Wang et al. 2016a). According to the argument of Kochanek (2014), stars with initial masses $\lesssim 17M_\odot$ can experience failed explosions and evolve to BHs. Wang et al. (2016a) showed that short orbital-period BH low-mass X-ray binaries can be effectively produced through the standard CE scenario if most BHs are born in failed SNe. It has been long known that the pre-SN core structure of a massive star greatly determines the final fate of either explosion or implosion (Burrows et al. 1995). Recently, numerical simulations (e.g., O’Connor & Ott 2011; Ugliano et al. 2012; Pejcha & Thompson 2015; Ertl et al. 2016; Sukhbold et al. 2016) showed that the landscape of neutrino-driven explosions is strongly manipulated by the final core structure of massive stars, and there is no clean threshold to separate the outcomes of either neutron stars (NSs) or BHs. Stars with masses $\sim 15$–$21M_\odot$ still have the potential to eventually implode to a BH; on the contrary, a star more massive than $20M_\odot$ may successfully explode to become an NS (Raithel et al. 2018).

In this work, we perform binary population synthesis (BPS) calculations to simulate the Galactic population of BH binaries with normal-star companions. The main goal of this work is to estimate the number and parameter distribution of BH binaries that can be potentially discovered through optical observations of the normal-star companions. We here only consider the detached systems without the occurrence of Roche lobe overflow. In a forthcoming study, we will discuss the population of mass-transferring BH systems (i.e., X-ray binaries) in the Galaxy. The remainder of this paper is organized as follows. In Section 2, we introduce the BPS method, according to which we can generate a large number of BH binaries with normal-star companions. We present the calculated results and discussions in Section 3. We conclude in Section 4.

2. Method

The X-ray emission in detached systems should be very weak and even undetected due to little accretion onto the BHs. The BH masses in such binaries, however, can still be measured from the motions of the optical companions. In order to obtain the potential population of detached BH binaries with a normal-star companion in the Galaxy, we employ the population synthesis code BSE originally developed by Hurley et al. (2002). With BSE we can simulate the evolution of millions of binary stars with different initial parameters. The binary evolution is assumed to start from primordial binaries with two zero-age MS stars, and the subsequent evolution will be subject to many physical processes, e.g., mass and angular momentum transfer, CE evolution, BH formation, and natal kicks. A modification of the code was made by Shao & Li (2014).

We only consider detached BH binaries formed through the evolution of isolated binaries, that is, systems formed through dynamical interactions in global clusters are not included. During the evolution of the primordial binaries, the primary star first evolves to expand, then transfers mass to the secondary. Thus one first needs to determine whether the mass transfer is dynamically stable. This is critically dependent on the mass ratio of the primary and secondary stars and the mass accretion efficiency of the secondary star. Shao & Li (2014) built three mass-transfer modes to deal with the mass exchange between binary components, among which the rotation-dependent mode (assuming the accretion efficiency of the secondary to be dependent on its rotating velocity) appears to better reproduce the observed parameter distribution of Galactic binaries including BH–Be star systems (Shao & Li 2014), Wolf–Rayet star–O-type star systems (Shao & Li 2016), and NS–NS systems (Shao & Li 2018). Thus we adopt the rotation-dependent mass-transfer mode, in which the accretion efficiency of the secondary can be as low as $<0.2$ and the corresponding mass ratio of the primary to the secondary for stable mass transfer can reach $\sim 6$ (Shao & Li 2014). Compared with the traditional conservative mass transfer, this allows a much larger parameter space for stable mass transfer in the primordial binaries.

The binaries experiencing dynamically unstable mass transfer will go into CE evolution. The orbital energy of the embedded binary is used to eject the envelope. We adopt the standard energy conservation equation (Webbink 1984) to deal with the orbital decay, taking the binding energy parameter $\lambda$ calculated by Xu & Li (2010), and the CE ejection efficiency $\zeta_{\mathrm{CE}}$ is assumed to be unity. After CE evolution, the remnant binaries may survive if they do not merge during the spiral-in stages. Stellar mass-loss rates of Hurley et al. (2000) are employed, except for hot OB stars, for which we apply the simulated rates of Vink et al. (2001). When the entire envelope of the primary star is stripped due to binary interactions, we reduce the mass-loss prescription of Hamann et al. (1995) by a factor of 2 for helium stars (Kiel & Hurley 2006).

At their formation, the BHs may be imparted a natal kick, resulting in eccentric orbits or even disruption of the binary systems. The SN processes play a vital role in determining both the magnitude of the kick velocities and the weight of the BH masses. In order to account for the $\sim 2$–$5M_\odot$ gap between NS and BH masses, Fryer et al. (2012) proposed the rapid SN mechanism assuming that the final mass of a compact object is contributed by the proto-compact object and the fallback material. With this mechanism, stars with masses $\gtrsim 20M_\odot$ could evolve to BHs. More recently, Sukhbold et al. (2016) suggested that stars with masses as low as $15M_\odot$ have a chance to implode to be a BH, and the average likelihoods for stars with initial masses of $15$–$40M_\odot$ and $45$–$120M_\odot$ were respectively 0.574 and 0.656 (Raithel et al. 2018). In this case the BH masses were directly obtained as the remnant masses of pre-SN stars, or the combined masses of the helium core and a small fraction ($\lesssim 0.1$) of the envelope if it exists. In our simulations we consider both prescriptions to deal with the BH masses. The first one is $M_{\mathrm{BH}} = 0.9 (M_{\mathrm{proto}} + M_\odot)$, where $M_{\mathrm{proto}}$ and $M_\odot$ are respectively the masses of the protocompact object and the fallback material. The other one is $M_{\mathrm{BH}} = 0.9 M_{\mathrm{rem}}$, where $M_{\mathrm{rem}}$ is the pre-SN remnant masses. Note that the pre-SN primaries in our BPS calculations are always helium stars without any hydrogen envelope due to binary interactions.

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4 Frigos et al. (2019) simulated the inspiral of a $1.4M_\odot$ NS inside the envelope of a $12M_\odot$ red supergiant star and suggested a very high $\alpha_{\mathrm{CE}}$-equivalent efficiency of $\approx 5$. Also, Mapelli & Giacobbo (2018) showed that the cosmic merger rates predicted for NS–NS binaries are consistent with LIGO-Virgo estimations when adopting $\alpha_{\mathrm{CE}} = 5$ in population synthesis models. If the $\alpha_{\mathrm{CE}}$ is indeed higher than unity, it could help resolve the formation problem of BH low-mass X-ray binaries (Podsiadlowski et al. 2003; Kiel & Hurley 2006; Yungelson & Lasota 2008).

5 Note that the other method of the delayed SN mechanism in Fryer et al. (2012) allows the formation of low-mass BHs, so is not included in our calculations.

6 The value of 0.9 denotes the efficiency of converting baryonic to gravitational masses (e.g., Timmes et al. 1996).
and the stars with $M_{\text{rem}} = 5M_\odot$ have initial masses close to $15M_\odot$. Following the suggestion of Raithel et al. (2018), we assume that all pre-SN primaries with masses larger than $5M_\odot$ have a probability of 0.6 of forming BHs.

For BH natal kicks in the former situation, we use the NS kick velocity reduced by a factor of $(1 - f_{\text{fb}})$, where $f_{\text{fb}}$ is the fallback material fraction (denoted as Model A). Here the kick velocity for NSs is assumed to follow a Maxwellian distribution with a dispersion of $\sigma_k = 265$ km s$^{-1}$ (Hobbs et al. 2005). In the latter scenario, in which the BH formation does not involve the fallback process, we explore three variations of the BH natal kicks: (1) using the NS kick velocity reduced by a factor of $(3M_\odot/M_{\text{BH}})$ (denoted as Model B); (2) obeying a Maxwellian distribution with a dispersion of $\sigma_k = 150$ km s$^{-1}$ (denoted as Model C); (3) adopting a Maxwellian distribution with a smaller dispersion of $\sigma_k = 50$ km s$^{-1}$ (denoted as Model D).

[Figure 1. Distributions of BH mass $M_{\text{BH}}$ as a function of the initial mass $M_i$ of the primary star. The four panels correspond to Models A−D. In each panel, the black dots (with a number of $5 \times 10^3$) represent the output of the BPS calculations, and the red curve corresponds to the BH-mass spectrum for single-star evolution.]

7 In this model, the kick velocities are assumed to be inversely proportional to the BH masses, and the minimum BH mass is set to be $3M_\odot$ (Wang et al. 2016a).

We simulate the evolution of the primordial binaries by setting the initial parameters as follows. For the primary stars, we use the initial mass function (IMF) given by Kroupa et al. (1993). For the secondary stars, we assume a flat mass ratio distribution between 0 and 1. The distribution of initial orbital separations is assumed to be logarithmically flat (Abt 1983). We set the initial orbits of all binaries to be circular, as the outcome of the interactions of systems with the same semilatus rectum is almost independent of eccentricity (Hurley et al. 2002). We assume all stars are initially in binaries. The primordial binaries are thought to follow the distribution of stars in the Galaxy and the BH binaries are simply assumed to be close to their birth locations without considering possible motions. The initial metallicity of stars is set to be 0.02. Considering the star formation history of the Galaxy, we adopt a constant star formation rate of $3M_\odot$ yr$^{-1}$ over the past 10 Gyr period (Smith et al. 1978; Diehl et al. 2006; Robitaille & Whitney 2010).

If a primordial binary evolves through a phase that is identified to be a detached BH system, then such a binary
makes a contribution to the birth rate of the specific type of detached BH system. We follow the method of Hurley et al. (2002) to calculate the birth rate for each type of detached BH binary generated by our BPS calculations, which depends on the star formation rate of the Galaxy and the initial parameters of the primordial binaries.

3. Results and Discussions

3.1. Mass Spectrum of Newborn BHs

In Figure 1 we show the distributions of BH mass $M_{\text{BH}}$ as a function of the initial mass $M_i$ of the primary star. The four panels correspond to the adopted models A–D. In each panel, the black dots (with a number of $5 \times 10^3$) represent the output of the BPS calculations, and the red curve represents the BH-mass spectrum for single-star evolution. In all four panels, there is a dip in the red curve around $50 M_\odot$, which is caused by the very strong winds from luminous blue variables. For stars more massive than $50 M_\odot$, the BH-mass spectra in both the single and binary evolution cases are broadly consistent with each other; for stars less massive than $50 M_\odot$, the BHs evolved from single stars are generally more massive than those from binary evolution, as the mass transfer in the primordial binaries decreases the mass of the primary stars. However, in Model A, there is an abrupt step at $23 M_\odot \lesssim M_i \lesssim 28 M_\odot$ in the case of single-star evolution and at $25 M_\odot \lesssim M_i \lesssim 40 M_\odot$ in the case of binary evolution, corresponding to the process of direct collapse in the rapid SN mechanism (Fryer et al. 2012; See also Spera et al. 2015). We obtain $M_{\text{BH}} \sim 5$–16$M_\odot$ in all the models. Spera et al. (2015) used the population synthesis code SEVN to track the stellar evolution and obtained the mass spectrum of stellar-mass BHs. Applying the rapid SN model, Spera et al. (2015) derived the masses of BHs in the range of $\sim 6$–25$M_\odot$. This difference may originate from the different treatment of stellar winds.

3.2. Formation of Incipient BH Binaries

An incipient BH binary is a binary system just after the BH formation. Usually, the companion is an MS star. Based on the BPS calculations, we create several $10^5$ incipient BH binaries in each model, then pick out the systems with orbital periods less than $10^3$ days. Figure 2 shows the calculated birth-rate distributions of the incipient BH binaries in the companion mass $M_c$ versus orbital period $P_{\text{orb}}$ plane in different models. The colors in each pixel are scaled according to the weight of the corresponding birth rates. The Astrophysical Journal, 885:151 (10pp), 2019 November 10 Shao & Li
produced in Model A. The initial masses of the BH progenitors in this model are larger than $\sim 25 M_\odot$, so low-mass secondaries are not able to eject the primary’s envelopes during CE evolution (see also Podsiadlowski et al. 2003; Wang et al. 2016a), leading the binary system to merge to be a single star. Almost all of the incipient BH systems produced in Model A are the descendants of the primordial binaries experiencing stable mass transfer during the evolution. The companion masses distribute in the range of $\sim 5$–$50 M_\odot$ and the orbital periods of $\sim 1$–1000 days, the overall birth rate in the Galaxy is about $9.0 \times 10^{-5} \text{yr}^{-1}$. In Model B, the minimum companion mass is $\sim 0.7 M_\odot$, and the total birth rate of incipient BH systems is $6.0 \times 10^{-5} \text{yr}^{-1}$. This is because the initial masses of the BH progenitors in this model decrease to $\sim 15 M_\odot$ (Raithel et al. 2018), so binaries with low-mass secondaries are able to survive CE evolution. When applying other kick

Table 1

| Models | $M_{\text{BH}}$ | $V_k$ | $R_{\text{birth}}(\text{yr}^{-1})$ | $N_{\text{BH-MS}}$ | $N_{\text{BH-*}}$ |
|--------|----------------|-------|-------------------------------|-----------------|-----------------|
| A      | $M_{\text{proto}} + M_{\text{fb}}$ | $\propto (1 - f_{\text{fb}})$ | $9.0 \times 10^{-5}$ | 470 (260) | 2.4 (1.7) |
| B      | $M_{\text{rem}}$ | $\propto 3.0/M_{\text{BH}}$ | $6.0 \times 10^{-5}$ | 4100 (340) | 160 (11) |
| C      | $M_{\text{rem}}$ | $\alpha = 150 \text{ km s}^{-1}$ | $4.5 \times 10^{-5}$ | 4300 (285) | 175 (12) |
| D      | $M_{\text{rem}}$ | $\sigma_k = 50 \text{ km s}^{-1}$ | $1.3 \times 10^{-4}$ | 12000 (926) | 595 (48) |

Note. The numbers of detached BH binaries with normal-star companions brighter than 20 mag are given in parenthesis.

Figure 3. Birth-rate distributions of incipient BH binaries in the Galaxy, as a function of companion-mass $M_c$, BH mass $M_{\text{BH}}$, orbital period $P_{\text{orb}}$, and eccentricity $e$. The colored curves correspond to different assumed models.
velocity distributions to the newborn BHs in Models C and D, the distributions of incipient BH binaries as a function of the companion mass, BH mass, orbital period, and eccentricity in Models A–D. In addition to no low-mass companions, Model A predicts that the BH masses have a peak distribution at \( \sim 7-8M_\odot \), and the binary systems tend to have nearly circular orbits. The reason is that most of BHs are formed through direct collapse without a natal kick. In the other three models, the incipient BH binaries unsurprisingly have similar parameter distributions. Note that the binaries containing lighter BHs tend to have higher birth rates due to the IMF. In the following, we will simulate the Galactic population of detached BH systems with normal-star companions by tracking the evolution of the incipient BH binaries until the companions fill their corresponding Roche lobes. For clarification, we only show the Galactic population of detached BH binaries in Models A and B, the calculated results for all models are summarized in Table 1.

### 3.3. Overall Population of Detached BH Binaries

A detached BH binary can be discovered through observation of the optical companion. Based on the BPS calculations, we can predict the distributions of some observational parameters including the apparent magnitude \( m_V \), the radial velocity semi-amplitude \( K \), and the astrometric signature \( \alpha \). We use the stellar-mass, surface luminosity, and effective temperature of the optical companions to yield the absolute magnitude \( M_V \) and the stellar color \( B-V \). By taking into account the interstellar extinction \( A_V \) in the \( V \) band, the apparent magnitude \( m_V \) is given as

\[
m_V = M_V + 5(2 + \log D_{\text{kpc}}) + A_V(D_{\text{kpc}}),
\]

where \( D_{\text{kpc}} \) is the distance of the binary from the Sun normalized by 1 kpc and we assume \( A_V(D_{\text{kpc}}) = D_{\text{kpc}} \) (see also Yalinewich et al. 2018; Yamaguchi et al. 2018). The radial velocity semi-amplitude \( K \) of the optical companions is

\[
K = \sqrt{\frac{G}{(1 - e^2)^{1/2}a^{-1/2}M_c \sin i}},
\]

where \( G \) is the gravitational constant, \( e \) is the eccentricity, \( a \) is the semimajor axis, and \( i \) is the orbital inclination of detached BH binaries with respect to the Sun. The orientation of binary systems is assumed to have a random distribution. The astrometric signature \( \alpha \) is given by

\[
\alpha = \frac{a_{\text{project}}}{D},
\]

where \( D = D_{\text{kpc}} \times 1 \text{kpc} \), and \( a_{\text{project}} \) denotes the projected semimajor axis of the companion’s orbits (see also Breivik et al. 2017; Mashian & Loeb 2017).

In Figure 4 we show the cumulative number distributions of detached BH binaries in the Galaxy when gradually increasing \( m_V \) by an interval of 1 mag. The black and red curves denote the results under the assumptions of Models A and B, and the solid and dashed curves correspond to the systems with MS and giant companions, respectively. We find that there are \~ 500 detached BH binaries in Model A and the number rises to \~ 4000 in Model B. The BH systems with MS companions dominate the overall population, with only a small percent of them having giant companions.

Figure 5 presents the calculated number distributions of all detached BH binaries in the Galaxy, as a function of the orbital period \( P_{\text{orb}} \), eccentricity \( e \), BH mass \( M_{\text{BH}} \), companion mass \( M_c \), astrometric signature \( \alpha \), and radial velocity semi-amplitude \( K \). The black and red curves correspond to Models A and B, and the solid and dashed curves denote the binaries containing MS and giant companions, respectively. In both models, the orbital periods distribute in a wide range of \~ 1–1000 days and quite a number of systems have nearly circular orbits. In addition, the \( K \) distributions have a peak at \~ 30–100 km s\(^{-1}\) and \( \alpha \) broadly distributes in the range of \~ 3–1000 \( \mu \)as. The main differences between Models A and B are the component masses: the companion masses are \( \geq 5M_\odot \) and the BH masses cluster \~ 7–8\( M_\odot \) in Model A, while both the companions and the BHs tend to have low masses (peaked at \~ 1\( M_\odot \) and \~ 5\( M_\odot \) respectively) in Model B.

### 3.4. Detectable Population of Detached BH Binaries

Due to the limitation of astronomical instruments, the very dark companions in detached BH binaries cannot be detected at present. Based on the current high performance of \textit{Gaia}, with a limiting magnitude of 20 mag in the \textit{G} band, we further discuss the detectable population of detached BH binaries in the \textit{Gaia} era. Following Yamaguchi et al. (2018) and Yalinewich et al. (2018), we equate the \textit{Gaia} band with the \textit{V} band for the optical companions. For testing the valid of this assumption, we have used the color–color transformations of Jordi et al. (2010) to compute the \textit{Gaia} \textit{G} magnitude, and find that the population size of detached BH binaries is increased by a factor of only a few percent. In Figure 6 we show the number distributions of detached BH binaries with optical companions brighter than 20 mag in the Galaxy, under the assumptions of Models A (black curves) and B (red curves). The solid and dashed curves correspond to the systems with MS and giant companions, respectively. We can see that a large number of binaries with low-mass companions are hidden and undetected, and the
number of detectable binaries drops to several hundreds in both models. We emphasize that there are still over 100 detectable detached BH binaries with companion masses less than \( \sim 5M_\odot \) in Model B.

Figures 7 and 8 present the number distributions of detectable detached BH binaries in the \( P_{\text{orb}}-e \) (left panels), \( M_{\text{BH}}-M_c \) (middle panels), and \( \alpha-K \) planes (right panels) in Models A and B, respectively. The top and bottom panels correspond to the systems with MS and giant companions, respectively. Each panel contains 40 \( \times \) 40 matrix elements, the colors reflect the number of detached BH binaries in the corresponding matrix element by accumulating the product of the birth rates with the time durations. Due to tidal interactions, the systems with \( P_{\text{orb}} \lesssim 3 \) days tend to have circular orbits if
the companions are still MS stars, while most binaries can be circularized if the companions have climbed to the giant branches. For the component masses, Model B particularly predicts that the low-mass \((\lesssim 3M_\odot)\) normal stars are usually orbited by light \((\sim 4.5-6.5M_\odot)\) BHs. There is a tendency that the larger the \(\alpha\), the longer the \(a\), and thus the smaller the \(K\).

Several groups (Breivik et al. 2017; Mashian & Loeb 2017; Yalinewich et al. 2018; Yamaguchi et al. 2018) have explored the prospect of discovering BHs in binaries by Gaia based on the motions of normal-star companions. Mashian & Loeb (2017) estimated the number of BH binaries that could be detected by Gaia over its five year mission to be nearly \(2 \times 10^5\). However, they did not consider the effects of some important factors such as interstellar extinction, BH natal kicks, and mass-transfer process during binary evolution. Breivik et al. (2017) reduced the number to be 3800–12,000 by taking into account detailed treatments relevant for the formation of BH binaries, but the effect of interstellar extinction was still not incorporated. Yamaguchi et al. (2018) added the effect of interstellar extinction, and the estimated number of detectable BH binaries

Figure 7. Predicted number distributions of detectable detached BH binaries in Model A. The left, middle, and right panels correspond to the systems distributing in the \(P_{\text{orb}}-e\), \(M_{\text{BH}}-M_c\), and \(\alpha-K\) planes, respectively. The top and bottom panels correspond to systems with MS and giant companions, respectively. The colors in each pixel are scaled according to the number of detached BH binaries.

Figure 8. Similar to Figure 7, but in Model B.
significantly decreased to $\sim 200$–1000. Furthermore, Yalinewich et al. (2018) showed that their models yield only dozens of detectable BH binaries with luminous companions.

When comparing our obtained population of detectable BH binaries with that by Yamaguchi et al. (2018) and Yalinewich et al. (2018), we need to point out that there are big differences in the treatment of the formation processes of the binary systems. (1) Before the formation of the BH binaries, the progenitor systems experience either CE evolution or stable mass-transfer phases. During the CE phases, both Yamaguchi et al. (2018) and Yalinewich et al. (2018) adopted a constant $\alpha_{\text{CE}} = 0.1$ (or 1.0) for the CE parameter in their BPS calculations. The BH systems with low-mass companions could be rarely generated if taking $\alpha_{\text{CE}} = 0.1$, while a fraction of BH binaries could have low-mass companions as the survivors of CE evolution if taking an abnormally large value of 1.0 for $\alpha_{\text{CE}}$, because numerical calculations show that $\lambda$ is usually significantly less than 1 for supergiant stars (e.g., Dewi & Tauris 2000; Podsiadlowski et al. 2003; Xu & Li 2010; Wong et al. 2014; Wang et al. 2016b). In our Model B, the initial masses of BH progenitors can be as low as $\sim 15M_\odot$, and more than 100 BH systems with low-mass companions can be created after CE evolution. (2) Both Yamaguchi et al. (2018) and Yalinewich et al. (2018) indicated that the companion masses are heavier than $\sim 8$–15$M_\odot$ due to mass accretion if the progenitor systems have experienced stable mass-transfer phases. These are similar to our results in Model A, but we obtain less massive companions with minimal masses of $\sim 5M_\odot$, as the rotation-dependent mass-transfer mode is adopted during primordial binary evolution. Compared to previous works, we further provide the characteristics of BH binaries with giant companions. The recent discovery of a candidate BH orbited by a low-mass giant (Thompson et al. 2019) seemed to require a formation channel involving a CE phase, as proposed in our Model B.

4. Conclusion

Based on a BPS method, we have simulated the Galactic population of detectable BH binaries with normal-star companions. Considering the uncertainties in BH formation physics and relevant natal kicks, we build four different models to explore the possible effects on the binary population. Model A involves the traditional theory of BH formation. In this model the initial masses of BH progenitors are $\gtrsim 25M_\odot$, and the primordial binaries with a low-mass secondary cannot survive the spiral-in phases when they go into CE evolution. The BH progenitor masses can drop as low as $\sim 15M_\odot$ in the other models, and this allows the formation of BH binaries with a low-mass companion. The predicted number of detectable BH binaries in Model A is about one order of magnitude lower than those in other models. When only changing the BH natal kicks in Models B, C, and D, the calculated numbers vary by a factor of less than 3. In addition, there may exist some extra factors that can influence the potential number of detectable BH binaries. We assume all stars are in binaries, while observations show that about 70% massive stars are actually in binary systems (Sana et al. 2012); this will slightly reduce the population size. We adopt a constant star formation rate of $3M_\odot$ yr$^{-1}$ in the calculations. Many groups (e.g., Smith et al. 1978; Diehl et al. 2006; Robitaille & Whitney 2010) obtained a star formation rate of the Galaxy that varied in the range of $\sim 1$–5$M_\odot$ yr$^{-1}$, and the actual rate is subject to slight variations along the Galactic age (Rocha-Pinto et al. 2000). These can also change the calculated number by a factor of a few.

Considering that Model A cannot produce detectable BH binaries with low-mass companions, we summarize our main results from the other models except Model A as follows:

1. The birth rates of incipient BH binaries in the Galaxy are in the range of $(4.5–13) \times 10^{-5}$ yr$^{-1}$ when considering different natal kick distributions for newborn BHs. The systems with companion masses larger than $\sim 5M_\odot$ dominate the incipient BH binaries, and the birth rate of the binaries with low-mass ($\lesssim 5M_\odot$) companions is of the order $10^{-6}$ yr$^{-1}$. These two groups are roughly separated by the evolution of primordial binaries experiencing either stable mass transfer or a CE phase.

2. The overall population of detectable BH binaries is dominated by the systems with relatively low-mass companions. We predict that the total number is over 4000. If only considering the systems with companions brighter than 20 mag (i.e., observable by Gaia), the number of detectable BH binaries reduces to about several hundred.

3. Our calculations show that there are more than 100 detached BH systems with giant companions in the Galaxy and among them at least 10 could be detected. Such binaries tend to have companions of mass $\lesssim 5M_\odot$ and BHs of mass 4.5–7$M_\odot$, whose features are consistent with those of the candidate BH binary with a giant companion recently discovered by Thompson et al. (2019).

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