Research in Astronomy and Astrophysics, 22:122002 (13pp), 2022 December https://doi.org/10.1088/1674-4527/ac995e

On the Neutron Star/Black Hole Mass Gap and Black Hole Searches

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Received 2022 September 8; revised 2022 September 30; accepted 2022 October 10; published 2022 November 16

Abstract

Mass distribution of black holes in low-mass X-ray binaries previously suggested the existence of a ∼2–5 $M_\odot$ mass gap between the most massive neutron stars and the least massive black holes, while some recent evidence appears to support that this mass gap is being populated. Whether there is a mass gap or not can potentially shed light on the physics of supernova explosions that form neutron stars and black holes, although significant mass accretion of neutron stars including binary mergers may lead to the formation of mass-gap objects. In this review, I collect the compact objects that are probable black holes with masses being in the gap. Most of them are in binaries, their mass measurements are obviously subject to some uncertainties. Current observations are still unable to confidently infer an absence or presence of the mass gap. Ongoing and future surveys are expected to build the mass spectrum of black holes which can be used to constrain the process of their formation especially in binaries. I describe the theoretical predictions for the formation of black holes in various types of binaries, and present some prospects of searching for black holes via electromagnetic and gravitational wave observations.

Key words: stars: black holes – stars: neutron – (stars:) binaries: general – (stars:) supernovae: general

1. Introduction

Stars with masses $\gtrsim 8$ $M_\odot$ are believed to undergo core collapse at the end of their lives and leave behind compact objects as either neutron stars (NSs) or black holes (BHs). The mass distribution of compact objects contains the imprints of the physics of core-collapse supernovae. Almost all NSs with mass measurements are in binaries (see Özel & Freire 2016, for a review), and more than 100 such NSs have been reported to date (Alsing et al. 2018; Shao et al. 2020) including those from gravitational wave transients (The LIGO Scientific Collaboration et al. 2021b). Recently, gravitational microlensing observations start to reveal the nature of possible NSs with measured lens masses (Kaczmarek et al. 2022). Based on electromagnetic observations, the maximal mass of NSs is ∼2 $M_\odot$ in the binary pulsars with a white-dwarf (WD) companion (Demorest et al. 2010; Antoniadis et al. 2013; Cromartie et al. 2020; Farr & Chatziioannou 2020) and it likely rises up to ∼2.4 $M_\odot$ in the eclipsing binaries with a main-sequence companion (Clark et al. 2002; Linares et al. 2018; Kandel & Romani 2020; Romani et al. 2022). These are agreement with the maximum stable NS mass inferred from gravitational wave observations of the first NS+NS merger GW170817 (Margalit & Metzger 2017; Rezzolla et al. 2018; Ruiz et al. 2018; Shibata et al. 2019). In gravitational wave transients except GW190814 and GW190425, the NS components have the masses of $\lesssim 2.2$ $M_\odot$ (The LIGO Scientific Collaboration et al. 2021a, 2021b, 2021c; Li et al. 2021; Zhu et al. 2022). Over 20 BHs have been identified in X-ray binaries since their dynamical masses are measured (Remillard & McClintock 2006; Casares & Jonker 2014). The mass distribution of these BHs indicates a minimal mass of ∼5 $M_\odot$ (Bailyn et al. 1998; Özel et al. 2010; Farr et al. 2011). Also, Özel et al. (2010) demonstrated that observational selection effects are unlikely to significantly bias the observed distribution of BH masses. It is thus suggested that there is an absence of BHs in the mass range of ∼2–5 $M_\odot$, which is referred to as the mass gap between the heaviest NSs and the lightest BHs.

It is firmly established that stellar masses have a smooth distribution (Salpeter 1955; Kroupa et al. 1993), the observed mass gap for compact objects implies a discontinuous dependence of the remnant masses with their progenitor masses. Some possible explanations for this gap emerge, involving a range of different supernova mechanisms (e.g., Fryer et al. 2012; Fryer et al. 2022; Ugliano et al. 2012; Kochanek 2014; Liu et al. 2021). Massive star observations show that most of them are born as members of binary and multiple systems (Sana et al. 2012; Kobulnicky et al. 2014; Moe & Di Stefano 2017). As a consequence, a significant fraction of compact objects are expected to undergo a binary interaction during their progenitor evolution, which complicates the understanding of massive-star evolution and supernova-explosion processes (Langer 2012). Binary population synthesis (see Han et al. 2020, for a review) methods include the modeling of stellar evolution and binary interactions, which are widely applied to explore the population properties of a specific type of binary systems. With this method, an early investigation on the mass distribution of compact remnants in Galactic X-ray binaries showed that the rapid supernova mechanism leads to the depletion of remnants in the 2–5 $M_{\odot}$ mass range while the delayed mechanism results in a continuous mass distribution between NSs and BHs (Belczynski et al. 2012). Moreover, this gap may appear if the vast majority of the binaries with low-mass BHs are disrupted due to a supernova-driven natal kick (Mandel et al. 2021). On the other hand, Kreidberg et al. (2012) suggested that the previously reported masses of BHs in low-mass X-ray binaries may be overestimated and actually fill the gap when considering possible systematic errors from the inclination measurements of the binary orbits. In addition, it is possible that NSs in low-mass X-ray binaries significantly increase their masses during mass-transfer episodes and therefore intrude into the gap via accretion-induced collapse (Gao et al. 2022). Further precise mass measurements of BHs in the current sample of low-mass X-ray binaries are needed to reassess the existence of the mass gap and settle the mechanism of supernova explosions (e.g., Casares et al. 2022).

In recent years, searching for BHs outside X-ray binaries has became a particularly active field of research. Theoretical studies predict that there are about 10^8 stellar-mass BHs in the Milky Way (e.g., Brown & Bethe 1994; Timmes et al. 1996), most of them are expected to appear as singles because of a binary disruption or a binary merger (Wiktorowicz et al. 2019; Olejak et al. 2020). Gravitational microlensing has been proposed to find dark compact objects over past decades (Paczynski 1986, 1996), and already extended to various searches of stellar-mass BHs (e.g., Bennett et al. 2002; Mao et al. 2002; Wyrzykowski et al. 2016). With gravitational microlensing, optical surveys have been carried out to probe a wide range of stellar-remnant masses (Wyrzykowski & Mandel 2020; Mróz et al. 2021; Mróz & Wyrzykowski 2021). In binary systems, radial velocity searches of optical companions have been proposed to discover quiescent BHs (Guseinov & Zel'dovich 1966; Trimble & Thorne 1969; Gu et al. 2019). Recently, a series of optical surveys are implemented to identify these types of BHs in the Galactic field (e.g., Liu et al. 2019; Thompson et al. 2019; Zheng et al. 2019; Rowan et al. 2021; Fu et al. 2022; Gaia Collaboration et al. 2022; Gomel et al. 2022; Jayasinghe et al. 2022; Mahy et al. 2022; Shahaf et al. 2022; Tanikawa et al. 2022), globular clusters (Giesers et al. 2018, 2019), and the Large Magellanic Cloud (Shenar et al. 2022a, 2022b). The discovery of the first binary BH merger GW150914 (Abbott et al. 2016) opens a new window to detect BHs in gravitational waves, and until now over 90 binary mergers with at least a BH component have been reported (Abbott et al. 2019, 2021a; The LIGO Scientific Collaboration et al. 2021a, 2021b, 2021c; Nitz et al. 2021). For some recently identified compact objects, there is growing evidence that the mass gap is being populated. It is predicted that ongoing and future surveys can greatly increase the number of the compact objects with mass measurements and build a mass spectrum to resolve the issue of mass gap.

This review is organized as follows. In Section 2, I collect the (candidate) BHs with masses in the gap from the literature (see also Figure 1) and briefly discuss their properties. I describe the formation scenarios of BH binaries in Section 3, and discuss the detection prospects for various types of Galactic BH binaries (see also Table 1) in Section 4.

2. Observations of Probable Mass-gap Black Holes

In Figure 1, I present the mass distribution of probable mass-gap BHs collected from the literature. A fraction of these BHs are observed in binaries with a nondegenerate companion, the BH masses can be dynamically measured according to the mass function

$$f(M) \equiv \frac{P_{\rm orb} K^3}{2\pi G} = \frac{M_{\rm BH} \sin^3 i}{(1+q)^2}, \quad (1)$$

where $P_{\rm orb}$ is the orbital period, K is the velocity semi-amplitude of the companion, $M_{\rm BH}$ is the BH mass, i is the inclination of the binary orbit, and q is the mass ratio of the companion to the BH. For a BH binary, spectroscopic observations can provide the radial velocity curve of the companion star, which is able to precisely yield the orbital period and the radial velocity semi-amplitude (see e.g., Casares & Jonker 2014; Thompson et al. 2019). So determining the BH mass requires that the inclination and mass ratio are securely constrained.

2.1. Low-mass X-Ray Binaries

2.1.1. 4U 1543-47

Spectroscopic observations of 4U 1543-47 reveal a radial velocity curve with an orbital period of ∼1.1 days and a semi-amplitude of ∼124 km s^{-1} (Orosz et al. 1998). The companion is classified as an A2 main-sequence star, corresponding to a mass of ∼2.3–2.6 $M_{\odot}$. For this binary, the orbital inclination is limited to the range of ∼20°–40°. The mass of the compact object is then calculated to be 2.7–7.5 $M_{\odot}$, suggesting that it is most likely a BH (Orosz et al. 1998) and probably in the mass gap.

2.1.2. GX 339-4

GX 339-4 has been studied frequently since its discovery (Markert et al. 1973; Heida et al. 2017, and references therein), which is suspected to contain a stripped giant and an accreting BH in a ∼1.7 days orbit (Muñoz-Darias et al. 2008). Dynamical mass of the BH reported by Muñoz-Darias et al. (2008) was more massive than about 6 $M_{\odot}$ (see also Hynes et al. 2003). Recently, Heida et al. (2017) carried out the observations of this source in quiescence and measured the radial velocity curve with the absorption lines from the companion star. Further data analyses revealed a mass function of

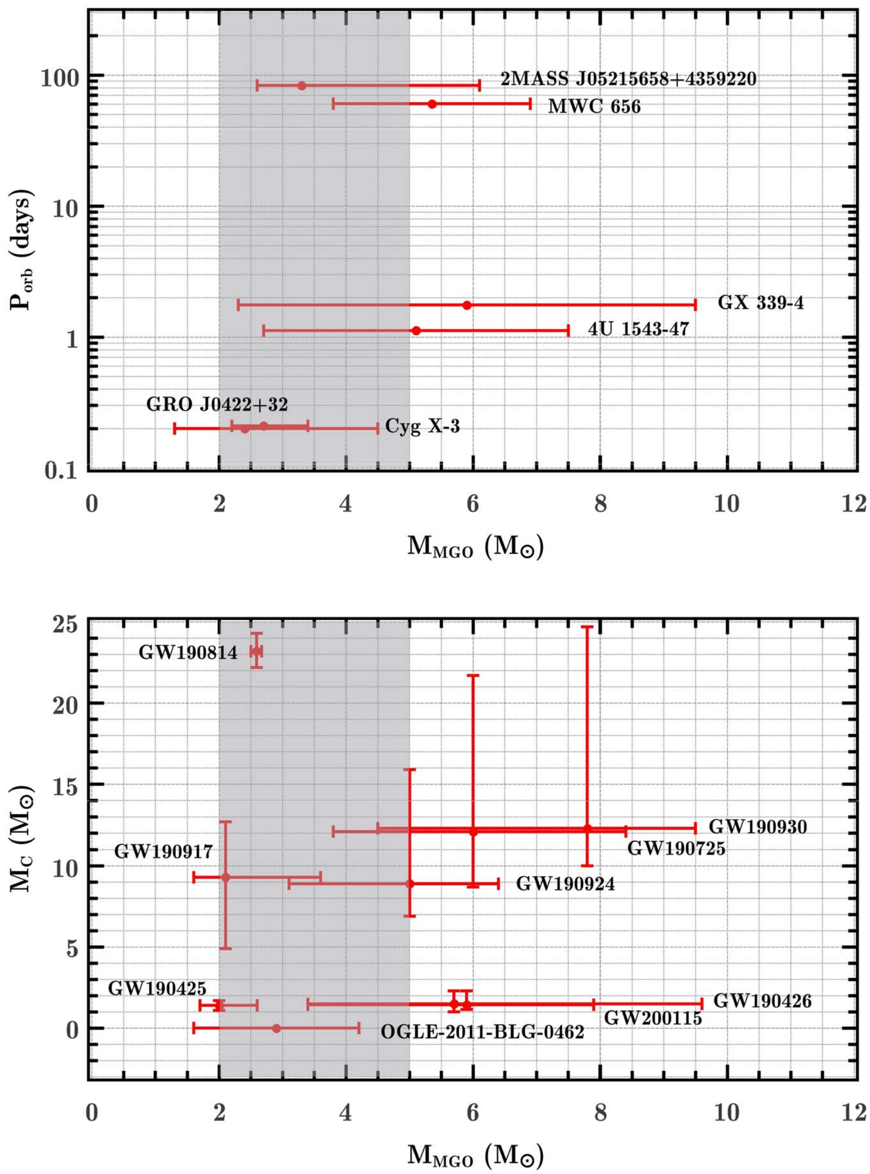

Figure 1. Top panel shows orbital period ($P_{\rm orb}$) as a function of mass ($M_{\rm MGO}$) for probable mass-gap objects in binaries. Bottom panel shows both component masses ($M_{\rm C}$ vs. $M_{\rm MGO}$) for gravitational wave transients with one component falling in the mass gap. This panel also includes the compact object detected in the gravitational microlensing event OGLE-2011-BLG-0462. The gray rectangle in each panel highlights the mass gap of 2–5 $M_{\odot}$.

$\sim$1.9 $M_{\odot}$, which lower than previously reported by a factor of about 3. The BH mass was finally constrained to 2.3–9.5 $M_{\odot}$, likely falling in the mass gap (Heida et al. 2017).

2.1.3. GRO J0422+32

GRO J0422+32 hosts an M-type main-sequence star and an accreting BH orbiting each other every $\sim$0.21 days. The orbital inclination of this binary has been frequently measured, covering a wide range of $\sim 10°$–$50°$ (Casares & Jonker 2014, and references therein). Note that all these inclinations are suspected since very large flickering amplitude is present in the optical/NIR light curves. A possible large inclination results in a lower limit of $\sim$2.2 $M_{\odot}$ for the BH mass (Webb et al. 2000). However, the big uncertainty from the inclination means that the BH mass can reach as high as $\gtrsim$10 $M_{\odot}$ (Reynolds et al. 2007). More recently, Casares et al. (2022) used a correlation between H_{α} trough depth and inclination to derive the inclination of $55.°6 \pm 4.°1$. Then the mass of the BH in this binary was constrained to be $2.7^{+0.7}_{-0.5}\, M_{\odot}$, placing it within the mass gap.

Table 1
Estimated Birthrates and Numbers for Various Types of BH Binaries in the Milky Way, by Assuming an Averaged Star Formation Rate of $\sim 3\ M_{\odot}\mathrm{yr}^{-1}$ over the Past 10 Gyr

Binary Types	R_{birth} (Myr^{-1})	N_{total}	N_{detect}
BH+MS	45–130	470–12000	260–930[a]
BH+G	⋯	2–600	2–50[a]
RLO XRB	⋯	50–820	⋯
BH+OB	⋯	110–440	10–30[b]
BH+Be	⋯	330–1000	⋯
BH+He	⋯	200–540	30–110[b]
BH+PSR	1–10	3–80	<8[c]
BH+BH	20–150	10^5–10^6	12–26[d]
BH+NS	4–30	10^4–10^5	2–14[d]
BH+WD	10–100	10^5–10^6	<38[d]

Notes. N_{total} and N_{detect} denote the total and detectable numbers of different types of Galactic BH binaries, respectively. The uncertainties of these numbers are mainly originated from the assumptions of different supernova models.
[a] BH+MS/BH+G represent detached BH systems with a main-sequence/giant companion, assuming they can be detected by Gaia if the optical companion is brighter than 20 mag (Shao & Li 2019).
[b] BH+OB/BH+He represent wind-fed X-ray binaries with a regular OB-star/helium-star companion, assuming they can be detected if their X-ray luminosities are larger than 10^{35} erg s^{-1} (Shao & Li 2020).
[c] BH+PSR represents the BH systems with a pulsar companion, assuming they can be detected by FAST with the flux density limit of 0.005 mJy in the telescope's visible sky (Shao & Li 2018a).
[d] BH+BH/BH+NS/BH+WD represent the BH systems with a BH/NS/WD companion, assuming they can be detected by LISA if the signal-to-noise ratio is larger than 5 (Shao & Li 2021b).

2.2. High-mass X-Ray Binaries

2.2.1. Cyg X-3

Cyg X-3 is the only known X-ray binary with a Wolf-Rayet donor in our Galaxy and this system has a short orbital period of ∼0.2 days (van Kerkwijk et al. 1992). The mass of the compact object was estimated by Zdziarski et al. (2013) to be $2.4^{+2.1}_{-1.1}\ M_{\odot}$, allowing for the presence of either an NS or a BH. The radio, infrared and X-ray properties of this source suggested that the compact object is more likely a BH (Zdziarski et al. 2013). Recent data analyses support that the compact object is probably a light BH but the estimation of its real mass is subject to many uncertainties (Koljonen & Maccarone 2017; Antokhin et al. 2022).

2.3. Detached Binaries with an Optical Companion

2.3.1. MWC 656

MWC 656 is a Be star probably associated with the gamma-ray source AGL J2241+4454 (Munar-Adrover et al. 2016). The analysis of optical photometry indicates a modulation with a period of ∼60 days, suggesting MWC 656 is a member of a binary system (Williams et al. 2010). Using the Be-star mass from its spectral classification and the mass ratio from the radial velocity curves of the Be star and the companion's disk, Casares et al. (2014) identified the dark companion as a BH with mass of 3.8–6.9 $M_{\odot}$. Contrary to Be/X-ray binaries with an accreting NS, it is interesting that the BH in this source is X-ray quiescent (see also Ribó et al. 2017). However, Rivinius et al. (2022) suggested that MWC 656 is more likely to host a hot subdwarf (i.e., an sdO+Be star binary, Shao & Li 2021a) instead of a BH.

2.3.2. 2MASS J05215658+4359220

Thompson et al. (2019) combined radial velocity and photometric variability data to show that the giant star 2MASS J05215658+4359220 orbits a massive unseen object every ∼83 days. Constraints on the giant's mass and radius implied that the unseen object has a mass of $3.3^{+2.8}_{-0.7}\ M_{\odot}$, suggesting it to be a low-mass BH within the mass gap. Follow-up X-ray observations of this source that yield an upper limit on X-ray emission indicated its nature of a noninteracting binary with a quiescent BH (Thompson et al. 2019). However, van den Heuvel & Tauris (2020) argued that the unseen object can be a close binary consisting of two main-sequence stars since this can naturally explain why no X-ray emission is detected.

2.4. Gravitational Microlensing Sources

2.4.1. OGLE-2011-BLG-0462

Gravitational microlensing has been proposed to detect isolated BHs in the Milky Way. When a BH lens passes between a source and observer, there is a transient brightening of the source due to gravitational microlensing. Recently, OGLE-2011-BLG-0462 has been reported to be the first discovery of a compact object with astrometric microlensing (Lam et al. 2022; Sahu et al. 2022). It was shown by Sahu et al. (2022) that the lens is a BH with mass of $7.1 \pm 1.3\ M_{\odot}$ and has a transverse space velocity of $\sim 45\ \mathrm{km\ s^{-1}}$ at a distance of 1.58 ± 0.18 kpc. Alternatively, Lam et al. (2022) suggested that the compact-object lens is either an NS or a BH with mass of 1.6–4.2 $M_{\odot}$ and it has a slow transverse motion of $<25\ \mathrm{km\ s^{-1}}$ at a distance of 0.69–1.75 kpc. Later, Mróz et al. (2022) proposed that systematic errors are a cause of the discrepant mass measurements and the lens should be a BH with mass of $7.88 \pm 0.82\ M_{\odot}$. Considering the compact object to be a BH, population synthesis simulations indicate that this BH more likely has a binary origin (Andrews & Kalogera 2022; Vigna-Gómez & Ramirez-Ruiz 2022).

2.5. Gravitational Wave Transients

2.5.1. GW190814 and Others

GW190814 contains a compact object of mass $2.59^{+0.08}_{-0.09}\ M_{\odot}$ that definitely lies in the mass gap (Abbott et al. 2020b). This compact object might be a very heavy NS or a very light BH (e.g., Huang et al. 2020; Most et al. 2020; Tsokaros et al. 2020; Zhang & Li 2020; Biswas et al. 2021; Bombaci et al. 2021; Godzieba et al. 2021; Zhou et al. 2021). Besides, seven other sources (GW190425, GW190426, GW190725, GW190917, GW190924, GW190930, GW200115) with false alarm rate of $<1 \mathrm{yr}^{-1}$ may also host a BH component within the mass gap (The LIGO Scientific Collaboration et al. 2021b). Interestingly, Bianconi et al. (2022) proposed that gravitational lensing is able to delay the arrival of gravitational-wave signals and alter their amplitudes, providing a possible explanation of the detection of mass-gap objects as gravitationally lensed mergers of binary NSs. However, no compelling evidence for lensing has been found from current gravitational wave signals (Abbott et al. 2021b).

3. Formation of Black Holes in Binaries

The general picture for the formation and evolution of isolated BH binaries has been well established over past decades (van den Heuvel 2009; Tauris & van den Heuvel 2023), including the evolutionary sequences from X-ray binaries (e.g., van den Heuvel 1975; Podsiadlowski et al. 2003; Belczynski et al. 2012; Zuo et al. 2014; Fragos & McClintock 2015; Qin et al. 2019; Shao & Li 2020) to double compact objects and gravitational wave sources (e.g., Tutukov & Yungelson 1993; Lipunov et al. 1997; Nelemans et al. 2001; Voss & Tauris 2003; Kalogera et al. 2007; Belczynski et al. 2016; Eldridge & Stanway 2016; van den Heuvel et al. 2017; Ablimit & Maeda 2018; Giacobbo & Mapelli 2018; Kruckow et al. 2018; Mapelli & Giacobbo 2018; Breivik et al. 2020; Shao & Li 2021b; Broekgaarden et al. 2021, 2022; van Son et al. 2022; Liotine et al. 222). In the canonical channel of forming BH systems, they are thought to stem from the primordial binaries with two zero-age main-sequence stars. It is required that the primordial binaries contain at least one massive star of $\gtrsim$15–25 $M_\odot$ for creating a BH (Woosley & Weaver 1995; Fryer et al. 2012; Kochanek 2014; Sukhbold et al. 2016; Raithel et al. 2018; Ertl et al. 2020; Mandel & Müller 2020).

Evolution of massive primordial binaries still remains some major uncertainties (Podsiadlowski et al. 1992; Langer 2012), such as the process of mass transfer between binary components. Depending on the structure of the primary donor, the mass ratio of the binary components and how conservative the mass transfer is, the binary systems are expected to undergo either a stable mass-transfer phase or a dynamically unstable mass-transfer phase (e.g., Soberman et al. 1997; Chen & Han 2008; Ge et al. 2010; Shao & Li 2014; Pavlovskii & Ivanova 2015; Pavlovskii et al. 2017; Ge et al. 2020; Marchant et al. 2021). Compared to stable mass transfer via Roche lobe overflow, dynamically unstable mass transfer can trigger common-envelope evolution, during which the binary orbit dramatically shrinks inside a shared envelope stemming from the donor and the orbital energy of the binary system is dissipated to unbind the common envelope (Paczynski 1976; Webbink 1984; Iben & Livio 1993; Ivanova et al. 2013). It is believed that the BH binaries with a low-mass ($\lesssim$1–2 $M_\odot$) secondary must have undergone a common-envelope phase while the ones with a high-mass ($\gtrsim$8–10 $M_\odot$) secondary more likely have experienced a stable mass-transfer phase (e.g., Podsiadlowski et al. 2003; Shao & Li 2020). As the evolutionary products of these BH binaries are totally different, I separately discuss the two cases in the following.

3.1. The Case of BH Binaries with a Low-mass Secondary

Figure 2 shows a schematic diagram for the formation and evolutionary track of a BH binary with a low-mass secondary. Since the primordial binary has an extreme mass ratio, the mass transfer between binary components is dynamically unstable and common-envelope evolution is unavoidable (e.g., Podsiadlowski et al. 2003). Considering that this binary can survive the common-envelope phase, the whole hydrogen-rich envelope of the primary star is successfully expelled. At the same time, the secondary star is expected to accrete hardly during the common-envelope evolution. The immediate binary hosts a massive Wolf-Rayet star and a low-mass main-sequence star. After the Wolf-Rayet star eventually collapses into a BH via a supernova explosion, this binary evolves to be a BH system with a low-mass secondary if it is not disrupted due to a supernova kick.[3] As a result, the initial orbit of this BH binary is usually eccentric. On the other hand, tidal interaction is able to circularize the binary orbit before the low-mass companion fills its Roche lobe. The source with a low-mass giant 2MASS J05215658+4359220 (Thompson et al. 2019) is probably such a detached BH binary formed in the canonical scenario as described above (see also Breivik et al. 2019; Shao & Li 2020). When Roche lobe overflow starts from the low-mass secondary to the BH, the system enters the stage of a low-mass X-ray binary. During this stage, stable mass accretion can result in efficient spin-up of the BH (King & Kolb 1999) and produce a significant BH spin consistent with observations (Podsiadlowski et al. 2003; Fragos & McClintock 2015; Shao & Li 2020). It is possible that the binary always appears as a low-mass X-ray binary within a Hubble time or evolves to be a detached BH system orbiting by a WD.

There is a long-standing problem for the formation of the BH binaries with a low-mass secondary (see Li 2015, for a review). Evolved from a primordial binary, its orbital energy may be insufficient to eject the whole envelope of the primary star during common-envelope evolution, given that the primary is more massive than ∼20–25 $M_\odot$ for creating a BH (Portegies Zwart et al. 1997; Kalogera 1999; Podsiadlowski et al. 2003;

[3] Observations of X-ray binaries indicate that BHs therein possess natal kick velocities of $\lesssim$80 km s^{-1} (Mandel 2016), with some possible exceptions (e.g., Fragos et al. 2009; Repetto et al. 2017).

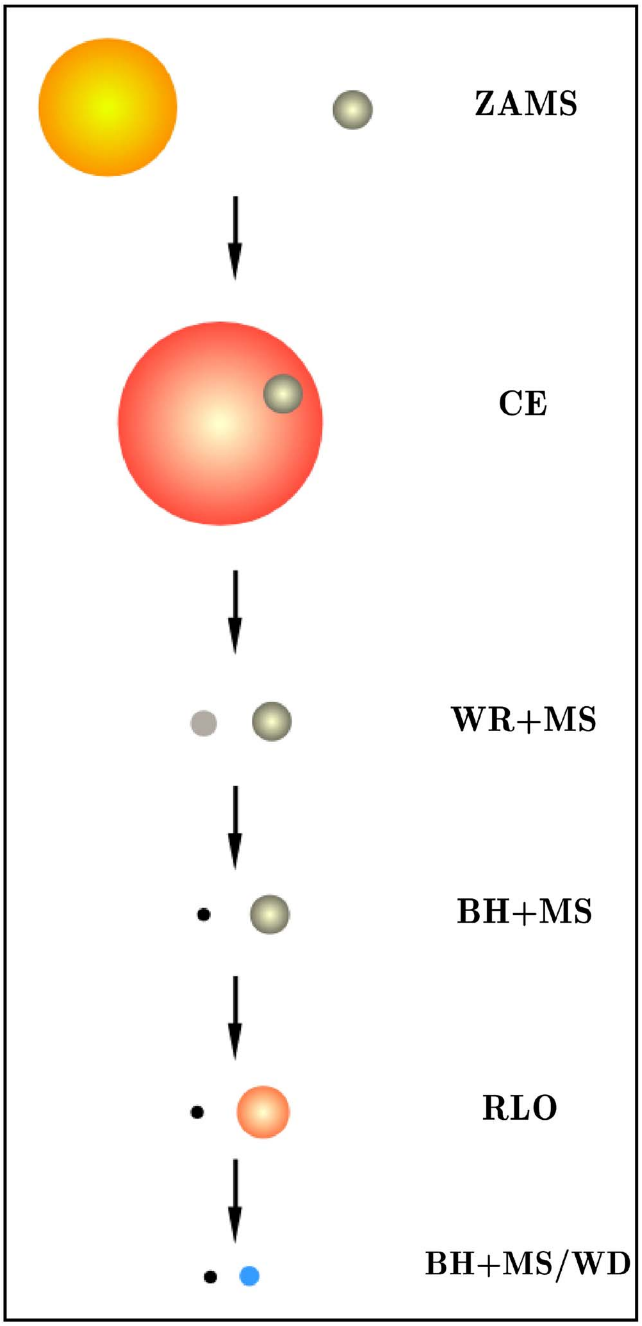

Figure 2. Illustration of the formation and evolution of a BH binary with a low-mass ($\lesssim$1–2 $M_\odot$) secondary, involving the evolutionary consequences of a detached system with a main-sequence companion, a low-mass X-ray binary and possibly a (detached) system with a white-dwarf companion. Acronyms used in this figure–ZAMS: zero-age main sequence; CE: common envelope; WR: Wolf Rayet; RLO: Roche lobe overflow; BH: black hole; WD: white dwarf.

Shao & Li 2020). Some exotic formation scenarios have been proposed to solve this problem, including triple star evolution (Eggleton & Verbunt 1986; Naoz et al. 2016), a low-mass companion originating from a disrupted envelope of the primary star (Podsiadlowski et al. 1995), the donor being a pre-main-sequence star (Ivanova 2006), the ejection of a massive envelope with additional nuclear energy (Podsiadlowski et al. 2010), or a dynamical origin involving fly-by stars in the Galactic field (Michaely & Perets 2016; Klencki et al. 2017). Besides, it is suggested that the BH binaries with a low-mass companion descend from those systems with an initially intermediate-mass companion as they are more likely to survive common-envelope evolution in the canonical formation scenario (Chen & Li 2006; Justham et al. 2006; Li 2008). In addition, a possible solution to this problem is enhancing the ejection efficiency for common-envelope evolution (Kiel & Hurley 2006; Yungelson & Lasota 2008). More recent investigations showed that the BH binaries with a low-mass secondary can effectively produced in the canonical scenario if assuming the BH's progenitors (i.e., the primary stars) have relatively small masses of $\gtrsim$15 $M_\odot$ (Shao & Li 2019, 2020). This assumption is consistent with some recent results according to numerical simulations of supernova explosions (e.g., Sukhbold et al. 2016; Raithel et al. 2018; Ertl et al. 2020). Furthermore, the mass distribution of BHs in low-mass X-ray binaries shows a rapid decline at the high-mass end of $\sim$10 $M_\odot$ (Özel et al. 2010). The narrow distribution of BH masses may provide clues to constrain the evolutionary path relevant to common-envelope phases (Wang et al. 2016), although significant mass increase of BHs is possible during the stage of X-ray binaries (e.g., Fragos & McClintock 2015).

Until now, most of confirmed BH systems in the Milky Way are low-mass X-ray binaries. These binaries always appear as transient sources with episodic outbursts, which are likely to be triggered by thermal and viscous instabilities in an accretion disk around the BH (van Paradijs 1996; Dubus et al. 1999; Lasota 2001; Coriat et al. 2012). For the long-term evolution of low-mass X-ray binaries, there exists a critical bifurcation orbital period of a few days (Pylyser & Savonije 1988, 1989) to separate them into converging and diverging systems. It is expected that diverging systems evolve to be wide binaries with a WD companion, while converging systems always contract to become tight X-ray binaries with a main-sequence donor. It is possible that the systems with orbital periods close to the critical value evolve to be tight BH binaries with a WD companion. These binaries may appear as detectable gravitational wave sources like tight NS+WD binaries that have been widely studied (Tauris 2018; Chen et al. 2020, 2021; Deng et al. 2021; Wang et al. 2021). Note that the real process of the evolution of BH low-mass X-ray binaries may be very complicated. Observations indicate that some such binaries are undergoing extremely rapid orbital decays, which are significantly larger than expected under the conventional mechanisms of magnetic braking and gravitational wave radiation (González Hernández et al. 2012, 2014, 2017). Extra mechanisms may also work during the evolution of BH low-mass X-ray binaries, e.g., the interaction of a binary with its surrounding circumbinary disk (Chen & Li 2015; Xu & Li 2018; Chen & Podsiadlowski 2019).

3.2. The Case of BH Binaries with a High-mass Secondary

Figure 3 shows a schematic diagram for the formation and evolutionary track of a BH binary with a high-mass secondary. In this case, both components of the primordial binary are massive stars that can eventually form BHs or NSs. During the evolution, the primary star first evolves to fill its Roche lobe and transfers its envelope to the secondary star. The mass transfer in such a binary can take place stably via the process of Roche lobe overflow. After mass transfer, the primary star loses its hydrogen envelope to become a Wolf-Rayet star and the secondary star increases its mass due to accretion. When the Wolf-Rayet star collapses into a BH, the immediate system is a BH binary with a high-mass secondary (e.g., MWC 656). In this binary, mass transfer starts as the secondary star fills its Roche lobe. As a result, the hydrogen envelope of the secondary is likely to be stripped by the BH via either stable Roche-lobe overflow or common-envelope evolution. The subsequent system contains a BH and another Wolf-Rayet star (e.g., Cyg X-3). As the Wolf-Rayet star ends its life as a BH or an NS, the final binary possesses two compact objects. If the system is tight enough, it may be observable as a gravitational wave source. Observations of BH+BH mergers indicate some BHs with high spins (The LIGO Scientific Collaboration et al. 2021b), which are spun up possibly via tidal interaction (e.g., Qin et al. 2018; Belczynski et al. 2020; Bavera et al. 2021; Fuller & Lu 2022) or stable mass transfer (van Son et al. 2020; Shao & Li 2022) during progenitor evolution.

During the evolution of massive primordial binaries, mass accretion can rejuvenate the secondary star (Hurley et al. 2002) and cause it to expand and spin up (Neo et al. 1977; Packet 1981). In the case of rapid mass accretion, the secondary star will get out of thermal equilibrium with significant expansion. This expanding secondary may even fill its own Roche lobe, leading to the formation of a contact system (Nelson & Eggleton 2001) and then probably a binary merger. Hence, the mass-transfer efficiency, i.e., the fraction of matter accreted onto the secondary among all transferred matter, is a key factor determining whether a binary system evolves into contact. This efficiency has been widely discussed in the literature (e.g., Vanbeveren et al. 1979; De Loore & De Greve 1992; Wellstein et al. 2001; Petrovic et al. 2005; de Mink et al. 2007; Shao & Li 2014, 2016). It is suggested that the secondary star with rapid rotation will suppress its mass increment and drop the mass-transfer efficiency (Petrovic et al. 2005; Stancliffe & Eldridge 2009). It is known that the rotation evolution of the secondary star is mainly controlled by the torques from mass accretion and tidal interaction (de Mink et al. 2013; Shao & Li 2014). In wide systems tidal effects can usually be neglected, while in close systems they tend to prevent the spin-up of the secondary star due to mass and angular momentum accretion. As a consequence, the mass-transfer efficiency is expected to be higher than ∼20% for close (Case A) binaries while drop to a level of

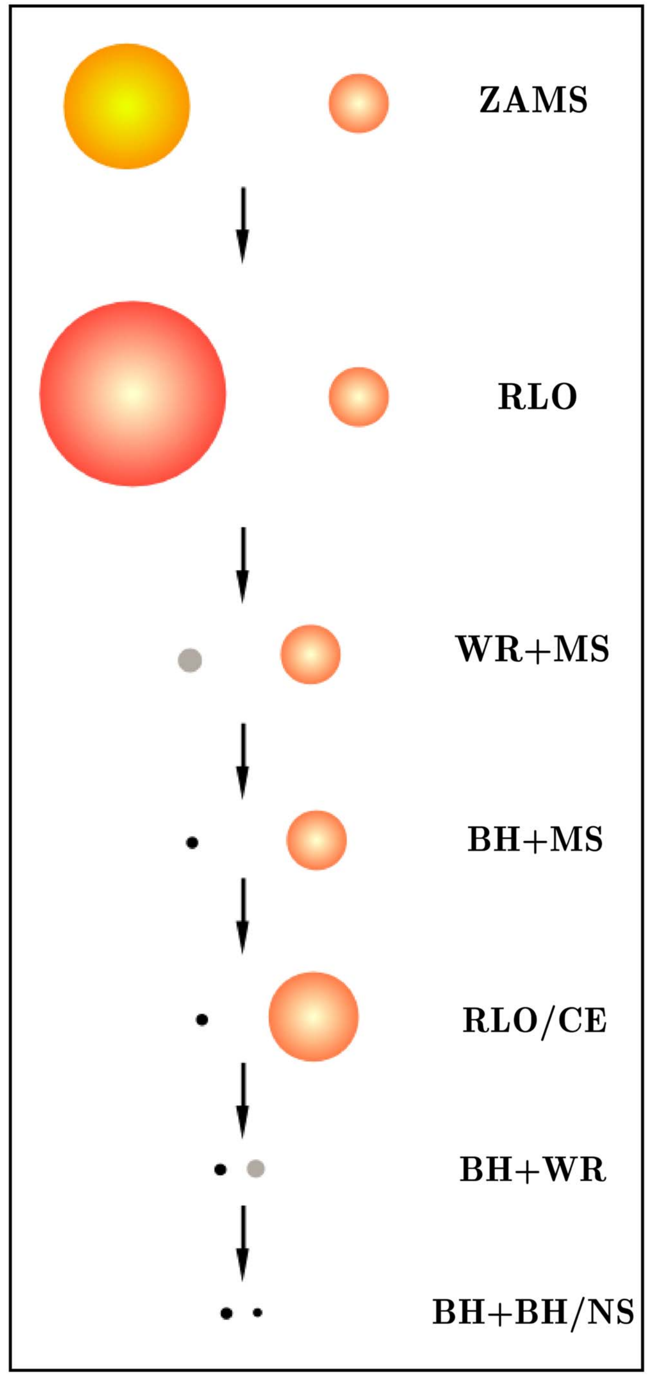

Figure 3. Illustration of the formation and evolution of a BH binary with a high-mass ($\gtrsim$8–10 $M_{\odot}$) secondary, involving the evolutionary consequences of a detached system with a main-sequence star, a high-mass X-ray binary with an OB star or a Wolf-Rayet star, and finally a BH+BH or BH+NS system.

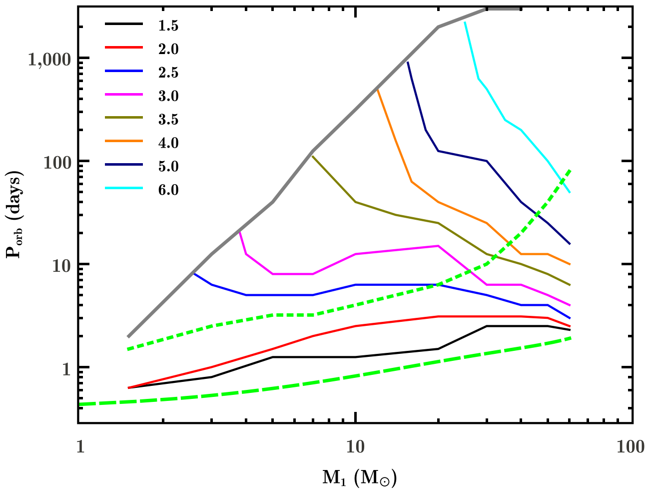

Figure 4. Allowed parameter spaces (solid curves) in the orbital period (P_{orb}) vs. primary mass (M_1) plane for stable mass transfer in which contact and common-envelope phases are avoidable, by assuming that the mass-accretion rate onto the secondary to be dependent on its rotating velocity (i.e., the mass-transfer rate multiplied by a factor of $(\Omega_K - \Omega)/\Omega_K$, where Ω and Ω_K are the angular velocity of the secondary and the corresponding Keplerian limit). The numbers next to each colored label represent the mass ratio of the primary to the secondary. The green dashed, green dotted, and gray solid curves correspond to the orbital periods when the primary overflows its Roche lobe at zero-age main sequence, the end of main sequence, and the end of Hertzsprung gap, respectively. Figure from Shao & Li (2014).

~10% or lower for wide (Case B) binaries (Shao & Li 2016; Langer et al. 2020). This rotation-dependent picture for mass-transfer efficiencies can well describe the formation of some massive binaries such as Wolf-Rayet star+O star systems (Petrovic et al. 2005; Shao & Li 2016) and BH+Be star systems (Shao & Li 2014). In this situation, the maximal mass ratio of the primary to the secondary for avoiding common-envelope evolution can reach as high as ~6 (see Figure 4 for more details). However, the mass distribution of Be stars with an NS or a subdwarf companion suggests a more higher efficiency of $\gtrsim$0.3 even for wide systems (Shao & Li 2014; Schootemeijer et al. 2018; Vinciguerra et al. 2020).

Mass transfer stability in the binaries with an accreting BH and a massive donor has been frequently discussed over past years, since it was applied to understand the formation channel of binary BH mergers (e.g., Inayoshi et al. 2017; Pavlovskii et al. 2017; van den Heuvel et al. 2017; Neijssel et al. 2019; Shao & Li 2021b; Gallegos-Garcia et al. 2021; Marchant et al. 2021; Olejak et al. 2021; Dorozsmai & Toonen 2022; van Son et al. 2022). In some cases, mass-transferring BH binaries with a massive donor are likely to undergo the expansion or convection instability that followed by common-envelope evolution (Pavlovskii et al. 2017). For relatively close systems, the expansion instability may take place when the donor stars are experiencing a period of fast thermal-timescale expansion. For relatively wide systems, the convection instability may happen if the donor stars have developed a sufficiently deep convective envelope. Pavlovskii et al. (2017) suggested that there exist the smallest radius R_U and the maximum radius R_S for which the convection and expansion instabilities can occur, respectively. With detailed binary evolution simulations, Shao & Li (2021b) ran a large grid of the initial parameters for the BH binaries with a massive donor to deal with mass transfer stability, and obtained thorough criteria for the occurrence of common-envelope evolution. These criteria are summarized as follows (see also Shao & Li 2021b). Mass transfer is always stable if the mass ratio q of the donor to the BH is less than the minimal value q_{min}, i.e.,

$$q < q_{min} \sim 1.5 - 2.0 \tag{2}$$

and always unstable if the mass ratio q is larger than the maximal value q_{max}, i.e.,

$$q > q_{max} \sim 2.1 + 0.8M_{BH}. \tag{3}$$

For the systems with $q_{min} < q < q_{max}$, dynamically unstable mass transfer ensues if the donor radius R_d is either smaller than R_S, i.e.,

$$R_d < R_S \sim 6.6 - 26.1q + 11.4q^2 \tag{4}$$

or larger than R_U, i.e.,

$$R_d > R_U \sim -173.8 + 45.5M_d - 0.18M_d^2. \tag{5}$$

Here all radii and masses are expressed in solar units. Figure 5 shows the detailed parameter-space distributions for mass-transfer stability in the BH binaries with a nondegenerate donor. It can be seen that the maximal mass ratios for avoiding common-envelope evolution are related to BH masses and there is a tendency that the binaries with heavier (lighter) BHs are more likely to undergo stable mass transfer (common-envelope evolution).

3.3. Formation of BHs from Accreting/merging NSs in Binaries

Mass increase of NSs may lead to their collapse into BHs, which process is likely to take place in various types of NS binaries with a nondegenerate-star or a compact-object companion (e.g., Vietri & Stella 1999; Dermer & Atoyan 2006; Yang et al. 2020; Gao et al. 2022; Qu & Liu 2022; Siegel et al. 2022). The standard picture for the formation and evolution of NS binaries is similar to the case of the BH binaries described above. It was proposed by Gao et al. (2022) that BHs can form from accretion-induced collapse of NSs in X-ray binaries. In this case, super-Eddington accretion is critical for the mass growth of NSs. Under this assumption, accretion-induced collapse of NSs may account for the formation of some mass-gap BHs observed in X-ray binaries like GRO J0422+32 (Gao et al. 2022). This case is supported by the observations that some NSs in redback and black-widow binaries can increase their masses to ~2.4 $M_\odot$ during previous mass accretion

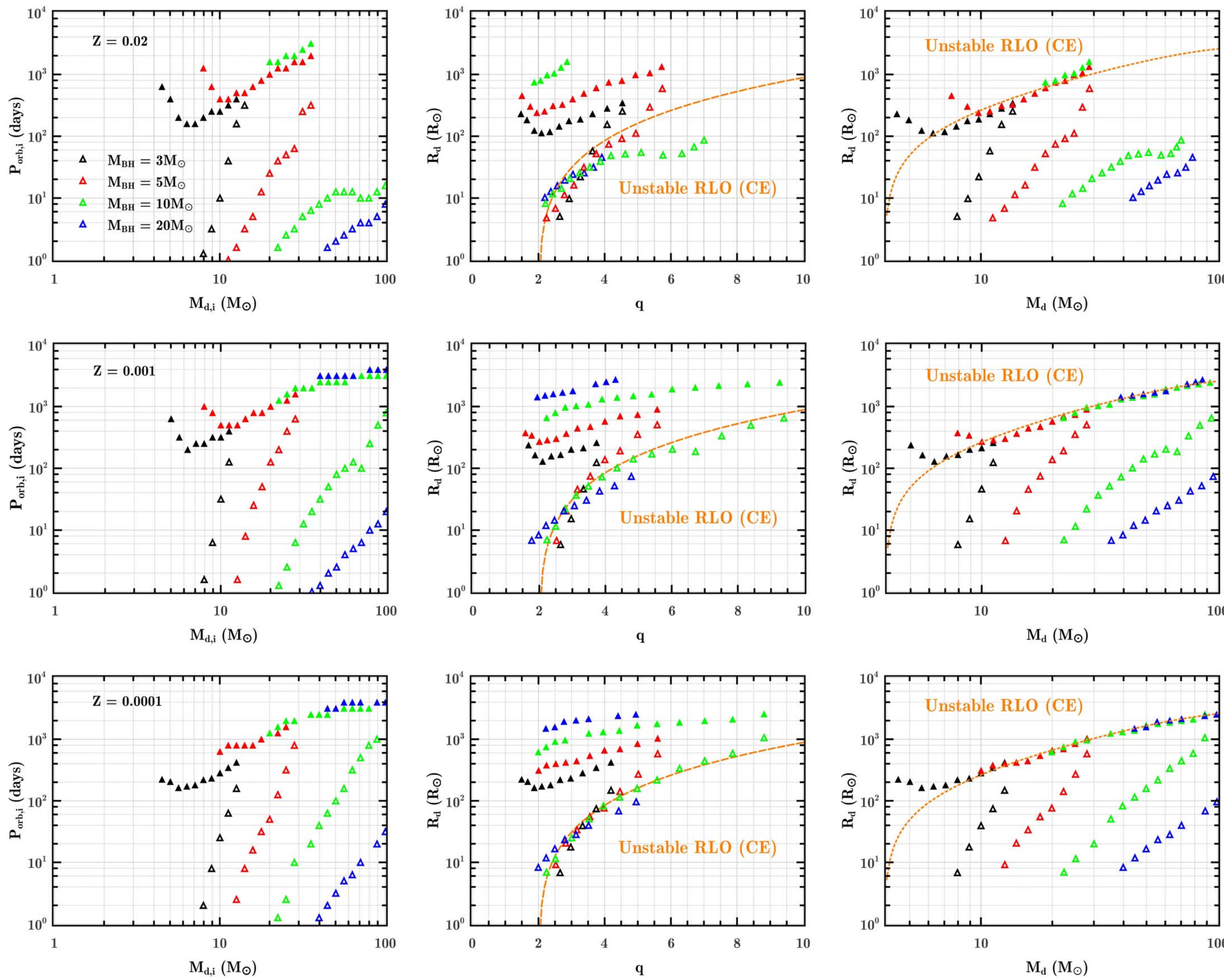

Figure 5. Parameter spaces for stable and unstable mass transfer in the BH binaries with nondegenerate donors at different metallicities (Z). The left panels show the parameter space outlines distributed in the donor mass−orbital period ($M_{d,i}$–$P_{orb,i}$) plane, while the middle and right panels correspond to the cases in the mass ratio −donor radius (q–R_d) and donor mass−donor radius (M_d–R_d) planes, respectively. The colored triangles in each panel denote the calculated boundaries for the binaries with different initial BH masses (M_{BH}), and the filled and open ones represent the upper and lower boundaries, respectively. The orange dashed curves roughly fit the lower boundaries of the donor radius as a function of the mass ratio, while the orange dotted curves for the upper boundaries as a function of the donor mass. Figure from Shao & Li (2021b).

(Linares et al. 2018; Kandel & Romani 2020; Romani et al. 2022).

For the NS binaries with a high-mass donor, dynamically unstable mass transfer seems to be unavoidable during the evolution since the extreme mass ratios of the binary components. During a common-envelope phase, a spiral-in NS may suffer from hypercritical accretion and then collapse into a BH (e.g., Chevalier 1993; van Son et al. 2020). It is complicated for the process of NS accretion if it develops an accretion disk and launches jets during the spiral-in stage (Soker & Gilkis 2018; Soker et al. 2019). On the other hand, recent hydrodynamical simulations reveal that an NS embedded in a common envelope only accretes very limited material with mass of $\lesssim 0.1\, M_\odot$ (MacLeod & Ramirez-Ruiz 2015), which are consistent with the mass distribution of the recycled pulsars in the tight binaries with a WD or an NS companion (e.g., Tauris et al. 2017). It is also possible that low-mass BHs are the remnants of binary NS mergers like GW170817 (Abbott et al. 2017) and GW190425

(Abbott et al. 2020a). There is a common feature that the cases of NS accretion and binary mergers are more likely to produce low-mass BHs within the mass gap.

4. Prospects of Searching for Black Holes

In this section, I mainly focus on a series of our recent works that assessing the detectability of various types of BH binaries including the detached systems with a main-sequence/giant companion (Shao & Li 2019), high-/low-mass X-ray binaries (Shao & Li 2020), the systems with a pulsar companion (Shao & Li 2018a), and the tight systems with a WD/NS/BH companion as gravitational wave sources (Shao & Li 2021b). Table 1 shows the estimated birthrates and numbers of these types of BH binaries in the Milky Way.

4.1. Detached BH Systems with a Main-sequence/giant Companion

Optical observations of visible stars in binaries with unseen objects have been proposed to hunt BHs (Guseinov & Zel'dovich 1966; Trimble & Thorne 1969; Gu et al. 2019). Identification of BHs by measuring their dynamical masses in this way has become a hot topic (e.g., Gould & Salim 2002; Breivik et al. 2017; Mashian & Loeb 2017; Yalinewich et al. 2018; Yamaguchi et al. 2018; Andrews et al. 2019; Shao & Li 2019; Yi et al. 2019; Shikauchi et al. 2020, 2022; Wiktorowicz et al. 2020; Chawla et al. 2022; Janssens et al. 2022). In part of detached binaries, BHs are accreting at a sufficiently low rate and therefore emitting undetectable X-rays. To date, a handful of binaries have been claimed to harbour a quiescent BH (e.g., Liu et al. 2019; Thompson et al. 2019; Jayasinghe et al. 2021; El-Badry et al. 2022b; Shenar et al. 2022b; Saracino et al. 2022). However, it is argued that most of these sources have been shown to be incorrect classifications and do not contain a BH (e.g., Shenar et al. 2020; van den Heuvel & Tauris 2020; El-Badry et al. 2022a; El-Badry & Burdge 2022).

Although the searches of non-interacting BHs are still challenging, there must have a number of detached BH binaries in the Milky Way. Using the method of binary population synthesis, Shao & Li (2019) simulated the Galactic population of detached BH binaries with a main-sequence/giant companion. According to the conventional wisdom, BHs evolve form stars of more massive than $\sim$20–25 $M_\odot$. As I have mentioned before, it is difficult to produce the BH systems with a low-mass companion in this case, since previous common-envelope phases always led to binary mergers. Adopting some recent suggestions (e.g., Sukhbold et al. 2016; Raithel et al. 2018) that the masses of BH's progenitors can reach as low as $\sim$15 $M_\odot$ and the remnant BHs have the masses of pre-supernova stars, Shao & Li (2019) estimated that $\sim$4000–12,000 detached BH systems can be produced in the Milky Way and hundreds of them are potentially observable systems by Gaia. Among all these detached BH binaries, the majority of them are expected to have a main-sequence companion while a small part of them contain a giant companion. Most notably, the BHs formed in this scenario tend to have relatively large masses of $\gtrsim$5 $M_\odot$ (Shao & Li 2019), allowing a presence of the mass gap.

4.2. BH X-ray Binaries

Since the discovery of the first X-ray source Scorpius X-1 outside the solar system (Giacconi et al. 1962), there are more than 300 X-ray binaries known in the Milky Way (Liu et al. 2006, 2007). For a significant fraction of X-ray binaries, the nature of accreting compact objects is unclear. Further data analyses and deep observations may reveal the properties of some hidden/candidate BHs in these existing X-ray binaries (e.g., Atri et al. 2022; Dashwood Brown et al. 2022). For known BH X-ray binaries, most of them are lobe-filling systems with a low-mass companion while only a few are wind-fed systems with a high-mass companion. In the latter case, the high-mass companion could be an OB (supergiant) star (e.g., Cyg X-1, Orosz et al. 2011), a Be star (e.g., MWC 656, Casares & Jonker 2014), or a Wolf-Rayet (helium) star (e.g., Cyg X-3, Zdziarski et al. 2013). Although these wind-fed binaries are detached, they may appear as bright and detectable X-ray sources if BHs are efficiently capturing companion's winds.

Based on the work of Shao & Li (2019) for detached BH systems, Shao & Li (2020) further followed the evolutionary tracks of the binaries and obtained the potential population of Galactic BH X-ray binaries. Adopting a range of input physical models for BH formation, it is estimated that the total number of the wind-fed systems with an OB star in the Milky Way is $\sim$500–1500, of which $\sim$3/4 have a Be star (assuming its rotational velocity larger than 80% of the Keplerian limit, Porter & Rivinius 2003) and $\sim$1/4 have a regular OB star (assuming its rotational velocity less than 80% of the Keplerian limit). In addition, there are totally $\sim$200–500 binaries with a BH and a helium star in the Milky Way. Among all wind-fed systems, only a small fraction are expected to be observable X-ray binaries. For the lobe-filling systems with a low-mass donor, it is estimated that their total number in the Milky Way is about several hundred.

4.3. BH Binaries with a Pulsar Companion

More than 40 years have passed since the discovery of the first binary pulsar B1913+16 (Hulse & Taylor 1975), and there are about two dozens known in the Milky Way (e.g., Tauris et al. 2017; Shao & Li 2018b). However, no binary systems with a BH and a pulsar have been detected so far. Detection of such binaries is a holy grail in astrophysics, not only because they can provide clues to constrain the evolution of massive binaries, but also they are very useful for testing relativistic gravity and possible new physics (e.g., Liu et al. 2014; Seymour & Yagi 2018, 2020; Ding et al. 2021; Liu & Lyu 2021; Su et al. 2021; Tong et al. 2022).

Using a population synthesis method, Shao & Li (2018a) modeled the formation of the binaries with a BH and an NS in the Galactic disk and obtained the birthrate of such systems to be $\sim$1–10 Myr^{-1}. Considering that NSs can be detected as radio pulsars only when they are still active and beamed toward the Earth, it is estimated that there exist $\sim$3–80 systems with a BH and a pulsar in the Galactic disk and around 10% of them could be observed by FAST (Nan et al. 2011) in the telescope's visible sky (Shao & Li 2018a). Although these binaries are very rare, they are more likely to host a mass-gap BH in some specific supernova models (Shao & Li 2021b).

4.4. Gravitational Wave Sources Containing at Least a BH Component

Mergers of BH+BH or BH+NS binaries may emit observable gravitational wave signals, which can be used to explore the supernova mechanisms that forms NSs/BHs and test the existence of mass gap (e.g., Shao & Li 2021b; Dabrowny et al. 2021; Wagg et al. 2022; Farah et al. 2022; Olejak et al. 2022). Most notably, the detection of GW190814 with a mass-gap object challenges the standard paradigm of massive binary evolution and compact-object formation (e.g., Zevin et al. 2020; Antoniadis et al. 2022). Consequently, this mass-gap object has been proposed to be the result of NS accretion/mergers in active galactic nucleus disks (Yang et al. 2020), globular clusters (Kritos & Cholis 2021) or hierarchical triple systems (Liu & Lai 2021; Lu et al. 2021; Cholis et al. 2022). Current gravitational wave observations still identified a relative dearth of binaries with component masses in the mass gap (The LIGO Scientific Collaboration et al. 2021b).

To study the impact of a possible mass gap on the population properties of merging BH binaries with a WD/NS/BH companion, Shao & Li (2021b) adopted three different supernova mechanisms to treat the compact remnant masses including the rapid (Fryer et al. 2012), the delayed (Fryer et al. 2012) and the stochastic (Mandel & Müller 2020) recipes. The rapid supernova mechanism can naturally lead to a mass gap, while the delayed and stochastic mechanisms allow the formation of compact objects within the mass gap. With the calculations of binary population synthesis, Shao & Li (2021b) estimated that the local merger rate density of all binaries with at least a BH component is about 60–200 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. In the Milky Way, dozens of merging BH systems are detectable by future space-based gravitational wave detectors, e.g., LISA (Amaro-Seoane et al. 2017), TianQin (Luo et al. 2016) and Taiji (Ruan et al. 2020). Compared to no low-mass BHs formed via rapid supernova mechanism, both delayed and stochastic mechanisms predicted that $\sim$100%/ $\sim$70%/$\sim$30% of merging BH +WD/BH+NS/BH+BH binaries are likely to have BH components within the mass gap (Shao & Li 2021b).

4.5. Single BHs

Besides binaries, gravitational microlensing observations of isolated BHs provide a golden opportunity for testing the existence of mass gap and constraining the mechanism of supernova explosions (e.g., Lam et al. 2020). On the one hand, population synthesis simulations reveal that the vast majority of Galactic BHs appear as singles (Wiktorowicz et al. 2019; Olejak et al. 2020). On the other hand, supernova kicks are capable to disrupt the binaries with low-mass BHs (Mandel et al. 2021) and accretion of NSs from a companion may result in the formation of low-mass BHs in binaries (e.g., van Son et al. 2020; Gao et al. 2022).

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 11973026) and the National Program on Key Research and Development Project (Grant No. 2021YFA0718500).

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