Influence of Irradiation-driven Winds on the Evolution of Intermediate-mass Black Hole X-ray Binaries

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Abstract

In young dense clusters, an intermediate-mass black hole (IMBH) may get a companion star via exchange encounters or tidal capture and then evolve toward the IMBH X-ray binary by the Roche lobe overflow. It is generally thought that IMBH X-ray binaries are potential ultraluminous X-ray sources (ULXs); hence, their evolution is very significant. However, the irradiation-driven winds by the strong X-ray flux from the accretion disks around the IMBHs play an important role in determining the evolution of IMBH X-ray binaries and should be considered in the detailed binary evolution simulation. Employing the models with the MESA code, we focus on the influence of irradiation-driven winds on the evolution of IMBH X-ray binaries. Our simulations indicate that a high wind-driving efficiency \( f = 0.01 \) for \( Z = 0.02 \), and \( f = 0.002 \) for \( Z = 0.001 \) substantially shortens the duration in the ULX stage of IMBH X-ray binaries with an intermediate-mass \( (5 M_\odot) \) donor star. However, this effect can be ignored for high-mass \( (10 M_\odot) \) donor stars. The irradiation effect \( (f = 0.01 \) or \( 0.002 \) markedly shrinks the initial parameter space of IMBH binaries evolving toward ULXs with high luminosity \( (L_X > 10^{40} \text{ erg s}^{-1}) \) and hyperluminous X-ray sources in the donor-star mass versus orbital period diagram. Furthermore, the irradiation effect results in an efficient angular momentum loss, yielding to IMBH X-ray binaries with relatively close orbits. In our simulated parameter space, about 1% of IMBH binaries would evolve toward compact X-ray sources owing to short initial orbital periods, some of which might be detected as low-frequency gravitational-wave sources.

Unified Astronomy Thesaurus concepts: Black holes (162); Gravitational waves (678); X-ray binary stars (1811); Stellar evolution (1599); Galaxy clusters (584)

1. Introduction

Stellar-mass black holes (BHs; \( \sim 10 M_\odot \)) are the evolutionary products of massive stars that have exhausted all their nuclear fuel. The first gravitational-wave (GW) event, GW150914, discovered by the advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO; Abbott et al. 2016a, 2016b) revealed that stellar-mass (\( \lesssim 100 M_\odot \)) BHs widely exist in the universe. Meanwhile, many observations have revealed supermassive BHs (\( \gtrsim 10^6 M_\odot \)) at the centers of most galaxies (Kormendy & Richstone 1995). A continuous BH mass spectrum would suggest the existence of a transition population with masses in the range of \( 100 M_\odot \lesssim M_{\text{BH}} \lesssim 10^6 M_\odot \), which are referred to as intermediate-mass BHs (IMBHs). Recently, the analysis of dynamical states of the globular cluster 47 Tucanae and NGC 6624 probed using pulsars provided evidences of the existence of IMBHs (Kiziltan et al. 2017; Perera et al. 2017).

The concept of IMBHs is tightly related to the ultraluminous X-ray sources (ULXs). ROSAT, Chandra, and XMM-Newton observed many ULXs with X-ray luminosities in the range of \( 10^{39}–10^{41} \text{ erg s}^{-1} \), which are off-nucleus X-ray sources in external galaxies (Fabbiano 1989; Roberts & Warwick 2000; Ptak & Colbert 2004; Fabbiano & White 2006). The Eddington luminosity of a stellar-mass BH accretor with a mass of \( 10 M_\odot \) is \((1.5−3.0) \times 10^{39} \text{ erg s}^{-1}\), depending on the chemical composition of the accreting material. Considering that the Eddington luminosity of an IMBH with a mass of \( 1000 M_\odot \) is \( \sim 10^{41} \text{ erg s}^{-1} \), Colbert & Mushotzky (1999) first proposed that the accretors in some high-luminosity ULXs are IMBHs. Furthermore, the cool thermal radiation signatures provided by the X-ray spectra in some ULXs are consistent with low inner-disk temperatures in the accretion disk models of IMBHs (Kaaret et al. 2003; Miller et al. 2003, 2004; Cropper et al. 2004; Feng & Soria 2011). In particular, observations for hyperluminous X-ray sources (HLXs; \( L_X > 10^{41} \text{ erg s}^{-1} \)) presented sound evidence for the existence of IMBHs. Several reliable HLXs are M82 X-1 (Matsumoto et al. 2001), S0/a galaxy ESO 243-49 HLX-1 (Farrell et al. 2009; Wiersma et al. 2010; Davis et al. 2011; Servillat et al. 2011; Sutton et al. 2012), Cartwheel N10 (Pizzolato et al. 2010), and CXO J122518.6 + 144545 (Jonker et al. 2010).

Portegies Zwart et al. (2004b) suggested that HLX M82 X-1 is a \( ~1000 M_\odot \) IMBH accreting from a \( 10–15 M_\odot \) donor star near the end of its main sequence or slightly evolved state. However, Patruno et al. (2006) found that a \( ~200–500 M_\odot \) IMBH accreting material from a \( 20–25 M_\odot \) giant companion via Roche lobe overflow can explain the observed phenomenon of HLX M82 X-1. HLX-1 near the spiral galaxy ESO 243-49 is currently thought to be the best candidate for an IMBH. BH accretion disk models have been used to fit the X-ray spectrum of HLX-1 (Davis et al. 2011; Servillat et al. 2011; Godet et al. 2012; Straub et al. 2014), where the IMBH mass was estimated to be \( \sim 10^2–10^3 M_\odot \) (see also Webb et al. 2012). On the basis of the optical spectroscopic observations, Soria et al. (2013) proposed that HLX-1 and its surrounding stars originated from either a disrupted dwarf galaxy or a nuclear recoil.

Physical collisions in young dense star clusters are frequent when the stellar density in the core is high (Quinlan & Shapiro 1987; Portegies Zwart et al. 1999). In this situation, it
is possible for an IMBH to form through runaway collision in 3–5 Myr (Portegies Zwart & McMillan 2002; Portegies Zwart et al. 2004a; Sakurai et al. 2017). In a young (≤10 Myr) star cluster with extreme density (ρ ∼ 10^5 M⊙ pc^{-3}) and many stars (N > 10^5), tidal or dynamical capture readily occurs (Portegies Zwart et al. 2004a; Baumgardt et al. 2006). As a result of tidal capture or exchange encounters, the main-sequence stars can spiral into and circularize around an IMBH (Hopman et al. 2004). As an example, the ULX source in the young cluster MGG-11 of starburst galaxy M82 is likely to be an IMBH accreting from a captured donor star, and ≳10% of similar clusters with IMBHs acquire a tidally captured star that had already been circularized (Hopman et al. 2004).

Through the evolutionary simulation of IMBH X-ray binaries formed in dense star clusters via tidal capture, Li (2004) found that IMBHs can appear as ULXs with luminosities exceeding 10^{40} erg s^{-1} over several Myr. Madhusudhan et al. (2006) calculated 30,000 binary evolution models of IMBH X-ray binaries and obtained two requirements for the donor stars captured by IMBHs to produce active ULXs with luminosities ≳10^{40} erg s^{-1}. First, the donor stars of the IMBHs must have a mass ≳8 M⊙. Second, the initial orbital separations of IMBH binaries after circularization should be about 6–30 times the radii of the donor stars when they are on the zero-age main sequence. N-body simulations showed that the tidal energy dissipation of stars in young star clusters can result in IMBH binaries like those mentioned above (Baumgardt et al. 2006).

In principle, the strong X-ray flux from the accretion disks around IMBHs should irradiate the surfaces of the donor stars and generate strong stellar winds (see also Ruderman et al. 1989; Tavani & London 1993). This irradiation effect cannot be ignored because of the high X-ray luminosities of IMBH X-ray binaries. In this work, we focus on the effect of irradiation-driven winds on the evolution of IMBH X-ray binaries and explore the initial parameter space of IMBH binaries (consisting of an IMBH and a companion star) that can evolve toward the observed ULXs.

2. Description of IMBH Binary Evolution

2.1. Binary Evolution Code

In this work, we simulate the evolution of IMBH X-ray binaries using a MESA binary update version (r10108) in the Modules for Experiments in Stellar Astrophysics code (MESA; Paxton et al. 2011, 2013, 2015). As an evolutionary beginning, IMBH binaries consisting of an IMBH (with a mass of M_{bh}) and a main-sequence companion star (with a mass of M_d) are thought to have already formed in circular orbits via exchange encounters or tidal capture in dense clusters. The IMBH is assumed to be a point mass with a constant mass of 1000 M⊙. We consider two metallicities of the donor stars, that is, Z = 0.02 and 0.001. The effective Roche lobe radius of the companion star satisfies (Eggleton 1983)

\[ R_L = \frac{0.49q^{2/3}}{a (0.6q^{2/3} + \ln(1 + q^{1/3}))}, \]

where a is the orbital separation and q = M_d/M_{bh} is the mass ratio of the IMBH binary. If the donor star fills its Roche lobe, the mass transfer rate is determined according to the prescription given by Ritter (1988). We execute additional models (see Sections 2.2, 2.3, and 2.4) using the files run_binaryExtras.f90 and run_starExtras.f90 (We also share these two files with the MESA community).

We perform many detailed binary evolution simulations of IMBH binaries. A donor star would be tidally disrupted when the separation to the IMBH is less than the tidal radius R_t = (M_{bh}/M_d)^{1/3} R_d. According to the law of conservation of orbital angular momentum, the circularization radius is a_{cir} ≈ (4–5) R_t after in-spiraling and circulation of the donor star (Hopman et al. 2004; Li 2004). Taking M_d = 1.0 M_⊙, we have a_{cir} ≈ (40–50) R_d, which corresponds to a minimum orbital period of 0.9–1.3 days. Blecha et al. (2006) obtained a wide range of separations (100–10^4 R_d) between captured donor stars and IMBHs: this range gives a maximum orbital period of several thousand days. Therefore, the donor-star masses and initial orbital periods are assumed to be M_{d,i} = 1–20 M_⊙ and log(P_{orb,i}/days) = 0–3.0 in the simulations.

2.2. Isotropic Winds

The donor star fills its Roche lobe when it thermally expands during the nuclear burning of the donor star or when angular momentum is lost from the binary system. The H-rich material on the surface of the donor star is transferred onto the IMBH. Because the mass growth of the IMBH can be ignored, the energy conversion efficiency η = 1 − \sqrt{1 − (M_{bh}/3M_{bh,0})^2} ≈ 0.06 (Podsiadlowski et al. 2003), where M_{bh,0} is the initial IMBH mass.

If the mass transfer rate is greater than the Eddington rate, the transferred matter exceeds the Eddington limit to be ejected in the vicinity of the IMBH. This material forms isotropic winds and carries away the specia lorbital angular momentum of the IMBH (Tauris & Savonije 1999).

2.3. X-ray Luminosity

There exist a high/soft state (with a soft and thermally dominated spectrum) and a low/hard state (with a nonthermal hard power law spectrum) in the observed spectrum of BH X-ray binaries (Nowak 1995). The transition between the low and high states should relate to a critical accretion rate M_{crit} (Körding et al. 2002). If the accretion rate M_{acc} > M_{crit}, the disk luminosity is directly proportional to M_{acc} like for a standard accretion disk; in contrast, the disk luminosity is directly proportional to \frac{M_{acc}}{M_{crit}} for the expected optically thin, advection-dominated accretion flow (Narayan & Yi 1995). The X-ray luminosity of the accretion disk can thus be written as (Körding et al. 2002)

\[ L_X = \begin{cases} \epsilon \frac{M_{acc}}{M_{crit}} c^2 M_{crit} < M_{acc} \leq M_{Edd} \\ \epsilon \frac{M_{acc}}{M_{crit}} M_{crit} c^2, M_{acc} < M_{crit} \end{cases} \]

\[ M_{crit} = 2.6 \times 10^{-5} \frac{M_{bh} \epsilon}{1000 M_⊙} \left( \frac{0.1}{\eta} \right) \left( \frac{1.7}{1 + X} \right) M_⊙ \text{ yr}^{-1}, \]
where $\epsilon$ is the radiative efficiency of the standard accretion disk. In this work, we take a typical critical accretion rate $\dot{M}_{\text{crit}} = 10^{-7} M_\odot \text{ yr}^{-1}$ (Narayan & Yi 1995; Hopman et al. 2004), and $\epsilon = 0.1$.

2.4. Irradiation-driven Winds

In a compact binary, the stellar wind from the donor star generated by X-ray radiation cannot be ignored during the accretion of the compact object (Ruderman et al. 1989; Tavani & London 1993). Additionally, because the accretion of the IMBH would produce an extremely high X-ray luminosity, the irradiation effect of X-ray flux on the surface of the donor star cannot be neglected for wide-orbit systems. A fraction of the X-ray flux that the donor star receives is assumed to overcome the gravitational potential energy and convert into the kinetic energy of the wind (where the velocity of the wind is thought to be the escape velocity at the donor’s surface), which are called the irradiation-driven winds. The stellar wind-loss rate therefore follows the relation

$$L_X \frac{\pi R_d^3}{4\pi a^2} f = -\frac{GM_d M_{\text{wind}}}{R_d},$$

where $R_d$ is the radius of the donor star and $f$ is the wind-driving efficiency. The irradiation-driven wind-loss rate is written as

$$\dot{M}_{\text{wind}} = -jL_X \frac{R_d^3}{4GM_d a^2}.$$

The irradiation-driven winds are assumed to be ejected from the vicinity of the donor star and carry away the specific orbital angular momentum of the donor star. The mass-loss rate of the donor star is $\dot{M}_d = \dot{M}_e + \dot{M}_{\text{wind}}$.

For donor stars with a metallicity $Z = 0.02$, we adopt three wind-driving efficiencies as $f = 0.01$, 0.001, and 0. Stars with different metallicities and different internal structures should have different wind-loss rates, and a modified factor $Z^{1/2}$ is thereby considered (Kudritzki et al. 1989; Hurley et al. 2000), i.e., the wind-driven efficiencies for the donor stars with a metallicity $Z = 0.01$ are taken to be $f = 0.002, 0.0002$, and 0.

3. Simulated Results

3.1. X-ray Luminosity

The evolutionary tracks of IMBH X-ray binaries with different initial donor-star masses and different initial orbital periods in X-ray luminosity versus mass transfer timescale diagrams are plotted in Figures 1 and 2 to illustrate the effect of irradiation-driven winds on the X-ray luminosities of IMBH X-ray binaries. The metallicities of the donor stars are $Z = 0.02$ and 0.001 in Figures 1 and 2, respectively. When $Z = 0.02$, the effect of a low wind-driving efficiency ($f = 0.001$) on the X-ray luminosities of IMBH X-ray binaries with a low-mass donor star is slight and can be ignored. At $Z = 0.001$, the X-ray luminosities of all IMBH X-ray binaries are hardly affected by the irradiation effect for a low wind-driving efficiency ($f = 0.0002$). For donor stars with a low-mass of $2 M_\odot$, it is difficult for IMBH X-ray binaries to appear as ULXs (when $Z = 0.001$, IMBH X-ray binaries with a short orbital period can appear as ULXs for 1.1 Myr), whereas they are visible as normal X-ray sources at a relatively long timescale of $\sim 50$–80 Myr, which depends on the initial orbital periods and metallicities. When the donor stars have an intermediate mass $(5 M_\odot)$ or a high mass $(10 M_\odot)$, a high wind-driving efficiency ($f = 0.01$ for $Z = 0.02$, and $f = 0.002$ for $Z = 0.001$) tends to produce a low X-ray luminosity. For high-mass donor stars, the effect of irradiation-driven winds can be neglected in the early stage of the mass transfer. All IMBH X-ray binaries have one or two gaps during the mass transfer. The gaps between two mass transfer stages originate from the thermal equilibrium deviation of the donor stars after their central hydrogen and helium are exhausted (see also Podsiadlowski et al. 2003; Kalogera et al. 2004; Li 2004; Rappaport et al. 2005).

Table 1 lists main evolutionary parameters of the IMBH X-ray binaries in Figures 1 and 2. To explore the effect of the X-ray irradiation process, two cases with wind-driving efficiency $f = 0$ and 0.01 (0.002 for $Z = 0.001$) are considered. When $Z = 0.001$, an IMBH X-ray binary with a low donor-star mass and short orbital period can appear as an ULX for $\sim 1$ Myr, while the irradiation effect hardly affects the duration of the ULX stage owing to the wind-driving efficiency being a low value of 0.002. All IMBH X-ray binaries with intermediate-mass $(5 M_\odot)$ or high-mass $(10 M_\odot)$ donor stars are visible as ULXs at $\Delta t_{\text{ULX}} \sim 0.1$–1.8 Myr. The irradiation effect obviously shortens the duration of the ULX stage for intermediate-mass donor stars, whereas its effect can be ignored for high-mass donor stars. Considering the irradiation effect, the durations of $\Delta t_{\text{ULX}}$ are also shortened by at least a factor of 2 for donor stars with metallicity of 0.02, while this effect is not evident for donor stars with metallicity of 0.01 owing to the low wind-driving efficiency. Two IMBH binaries with intermediate-mass donor stars ($P_{\text{orb},i} = 10$ days when $Z = 0.02$, and $P_{\text{orb},i} = 2.1$ days when $Z = 0.001$) do not evolve toward HLXs owing to the irradiation effect. For other systems, the irradiation effect obviously shortens the durations of the HLX stage.

3.2. Orbital Evolution and GW Sources

During the evolution of IMBH X-ray binaries, there is a bifurcation period, which is defined as the longest initial orbital period of a binary evolving into an ultracompact X-ray binary within the Hubble timescale (van der Sluys et al. 2005a, 2005b). The material transfer from the less massive donor star to the more massive IMBH would cause orbital periods to gradually increase, while the loss of angular momentum would produce an inverse tendency. The competition between orbital expansion and orbital shrinkage results in a competition period (Liu & Li 2017; Liu et al. 2021), which plays an important role in determining the final fate of a binary system including an accreting object (Podsiadlowski et al. 2002; Ma & Li 2009; Chen & Podsiadlowski 2016; Jia & Li 2016). Figure 3 shows evolutionary examples of IMBH binaries with initial orbital periods longer than the bifurcation period in the $P_{\text{orb}}$–$M_d$ diagrams. It is clear that the irradiation-driven winds strongly affect the orbital evolution of IMBH X-ray binaries. In particular, the irradiation-driven winds are ejected from the vicinity of the donor star and extract the specific orbital angular momentum expressed as follows:

$$j_u = \frac{JM_{\text{bh}}}{(M_{\text{bh}} + M_d) M_d}$$
where $J$ is the total orbital angular momentum of the binary. The isotropic winds during the super-Eddington accretion should be ejected from the vicinity of the IMBH, and the specific orbital angular momentum is thus given by

$$j_{\text{is}} = \frac{JM_d}{(M_{\text{bh}} + M_d)M_{\text{bh}}}.$$  

The ratio of these two values $j_{\text{is}}/j_{\text{bh}} = (M_{\text{bh}}/M_d)^2 \approx (1000/10)^2 = 10^4$, i.e., the efficiency of the extraction of angular momentum by the irradiation-driven winds is four orders of magnitude greater than that of the extraction of angular momentum by the isotropic winds. The irradiation-driven winds are therefore an important mechanism of angular momentum loss that affects the orbital evolution of IMBH X-ray binaries. When the donor stars (with a metallicity $Z = 0.02$) evolve into a mass $M_d \approx 1 M_{\odot}$, the orbital periods are approximately 20, 200, and 2000 days for a wind-driving efficiency $f = 0.01, 0.001$, and 0, respectively. For donor stars with low metallicity ($Z = 0.001$), the increasing rates of the orbital periods are obviously higher than those of the donor stars having $Z = 0.02$ when the irradiation effect is included. This difference likely originates from the relatively low wind-driving efficiency that we adopted for the donor stars with low metallicity.

If the initial orbital periods of IMBH binaries are shorter than the bifurcation period, these sources would evolve toward compact binary systems, which are potential Laser Interferometer Space Antenna (LISA) sources (Portegies Zwart et al. 2004b; Chen 2020). Figure 4 presents the evolution of IMBH binaries with a $2 M_{\odot}$ donor star and short orbital periods on a $P_{\text{orb}}-M_d$ diagram. The bifurcation periods are 1.4178 and 1.244

![Figure 1. Evolution of X-ray luminosity as a function of the mass transfer timescale for IMBH binaries with different initial donor-star (Z = 0.02) masses and initial orbital periods. The solid, dashed, and dotted curves denote the wind-driving efficiency $f = 0, 0.01$, and 0.001, respectively.](image-url)
days for a $2M_\odot$ donor star with metallicity of 0.02 and 0.001, respectively. The IMBH binaries with initial orbital periods much shorter than the bifurcation period tend to become compact binaries with relatively long orbital periods (see also Podsiadlowski et al. 2002; Chen & Podsiadlowski 2016; Chen 2020). When the initial orbital period equals the bifurcation period, the donor stars decouple their Roche lobes at $P_{\text{orb}} \approx 1.5$ days, and the IMBH X-ray binaries evolve into detached binaries with an IMBH and an He core ($\sim 0.2M_\odot$). Subsequently, the He core first evolves into an He white dwarf (WD) after a contraction phase and then enters a cooling stage (Istrate et al. 2014). Owing to the strong gravitational radiation, the orbits of the IMBH binaries rapidly shrink, and the IMBH binaries eventually evolve into ultracompact IMBH–WD binaries with orbital periods of 4.3 minutes in the Hubble timescale. For detached binaries consisting of a neutron star (NS) and a WD, only the systems with an initial orbital period less than 7–9 hr can become visible LISA sources (Tauris 2018; Chen et al. 2020, 2021). This difference arises from the masses of IMBHs being approximately three orders of magnitude higher than those of NSs, which results in a rate of angular momentum loss via gravitational radiation that is at least seven orders of magnitude higher than that in NS systems (see also Chen 2020). Our simulations also show that the wind-driving efficiency hardly affects the evolutionary tracks in Figure 4 (see also Section 3.3).

### 3.3. Initial Parameter of ULXs

The orbital period versus donor-star mass plane ($\log(P_{\text{orb},i}/\text{days}) = 0–3$ and $M_{d,i} = 1–20 M_\odot$, where $P_{\text{orb},i}$ and $M_{d,i}$ are, respectively, the initial orbital period and the initial
donor-star mass) is uniformly divided into $20 \times 15$ discrete grids, in which we diagnose whether the IMBH binaries evolve toward ULXs when the wind-driving efficiency $f = 0$ and $0.01$ (or $0.002$). Figure 5 shows the initial contours for ULXs with different maximum X-ray luminosities in the $\log P_{\text{orb},i} - M_{\text{d,i}}$ plane. It is clear that IMBH binaries with a low donor-star mass ($1-2 M_\odot$) and a short orbital period ($\sim 1-2$ days) cannot evolve toward ULXs. In Figure 5, the dashed–dotted curves denote the bifurcation periods. All IMBH binaries with an initial orbital period shorter than the bifurcation periods only appear as normal X-ray sources. Our simulations also show that the bifurcation periods are hardly affected by the wind-driving efficiency. The X-ray luminosities of these systems are relatively low (only $\sim 10^{39}$ erg s$^{-1}$), which results in a small irradiation-driven wind-loss rate and thus a small angular momentum loss rate. Both left and right panels have four grids under the bifurcation periods. This implies that about 1% of IMBH binaries in our simulated parameter space can evolve toward compact X-ray sources, with some appearing as low-frequency GW sources detectable by LISA (Chen 2020).

When considering the irradiation-driven winds, the left boundaries of the parameter spaces with $L_X > 10^{40}$ erg s$^{-1}$ and $L_X > 10^{41}$ erg s$^{-1}$ for $Z = 0.02$ move toward the high donor-star masses, whereas the lower and upper boundaries move

| $Z$  | $f$  | $M_{\text{d,i}}$ ($M_\odot$) | $P_{\text{orb},i}$ (days) | $t_{\text{dof}}$ (Myr) | $P_{\text{rolf}}$ (days) | $\Delta t_{\text{dof}}$ (Myr) | $\Delta t_{\text{rolf}}$ (Myr) | $\Delta t_{\text{rolf}}$ (10$^4$ yr) | $L_{X,\text{max}}$ ($10^{41}$ erg s$^{-1}$) |
|------|------|-----------------------------|---------------------------|------------------------|---------------------------|-------------------------------|-------------------------------|--------------------------------|----------------------------------|
| 0    | 0    | 2.0                         | 3.0                       | 986.89                 | 2.72                      | 0                             | 0                             | 0.001                           | 0.0006                           |
| 0.01 | 0    | 2.0                         | 10.0                      | 1016.09                | 9.96                      | 0                             | 0                             | 0.002                           | 0.0003                           |
| 0    | 0.02 | 5.0                         | 3.0                       | 84.53                  | 2.94                      | 1.756                         | 0.683                         | 0.5                             |                                  |
| 0.01 | 0.02 | 5.0                         | 10.0                      | 85.41                  | 9.99                      | 1.539                         | 0.426                         | 3.87                            | 2.4                              |
| 0    | 0.01 | 10.0                        | 3.0                       | 19.70                  | 2.97                      | 0.149                         | 0.149                         | 0.196                           | 0.32                             |
| 0.01 | 0.01 | 10.0                        | 10.0                      | 19.85                  | 9.997                     | 0.122                         | 0.086                         | 3.32                            | 2.8                              |
| 0.01 | 0.01 | 10.0                        | 10.0                      | 19.85                  | 9.997                     | 0.053                         | 0.025                         | 1.99                            | 2.4                              |
| 0    | 0    | 2.0                         | 2.1                       | 624.35                 | 1.77                      | 1.104                         | 0                             | 0.02                            |                                  |
| 0.002| 0    | 2.0                         | 2.1                       | 624.35                 | 1.77                      | 1.104                         | 0                             | 0.02                            |                                  |
| 0    | 0.002| 2.0                         | 5.2                       | 632.59                 | 5.13                      | 0                             | 0                             | 0.001                           |                                  |
| 0.002| 0    | 5.0                         | 2.1                       | 73.83                  | 2.01                      | 1.127                         | 0.304                         | 7.60                            | 1.8                              |
| 0.001| 0.002| 5.0                         | 2.1                       | 73.83                  | 2.01                      | 0.514                         | 0.266                         | 1.0                             |                                  |
| 0    | 0    | 5.0                         | 5.2                       | 74.26                  | 5.18                      | 1.427                         | 0.156                         | 6.91                            | 2.3                              |
| 0.002| 0    | 5.0                         | 5.2                       | 74.26                  | 5.18                      | 0.176                         | 0.106                         | 4.32                            | 2.2                              |
| 0    | 0.002| 10.0                        | 2.1                       | 20.82                  | 2.05                      | 0.150                         | 0.143                         | 7.52                            | 4.1                              |
| 0.002| 0    | 10.0                        | 5.2                       | 20.97                  | 5.19                      | 0.088                         | 0.081                         | 2.67                            | 2.8                              |
| 0.002| 0    | 10.0                        | 5.2                       | 20.97                  | 5.19                      | 0.084                         | 0.030                         | 2.37                            | 2.7                              |

| $Z$  | $f$  | $M_{\text{d,i}}$ ($M_\odot$) | $P_{\text{orb},i}$ (days) | $t_{\text{dof}}$ (Myr) | $P_{\text{rolf}}$ (days) | $\Delta t_{\text{dof}}$ (Myr) | $\Delta t_{\text{rolf}}$ (Myr) | $\Delta t_{\text{rolf}}$ (10$^4$ yr) | $L_{X,\text{max}}$ ($10^{41}$ erg s$^{-1}$) |
|------|------|-----------------------------|---------------------------|------------------------|---------------------------|-------------------------------|-------------------------------|--------------------------------|----------------------------------|
| 0    | 0    | 2.0                         | 4.1                       | 624.35                 | 2.72                      | 0                             | 0                             | 0.001                           | 0.0006                           |
| 0.002| 0    | 2.0                         | 5.2                       | 632.59                 | 5.13                      | 0                             | 0                             | 0.002                           | 0.0003                           |
| 0    | 0.002| 5.0                         | 2.1                       | 73.83                  | 2.01                      | 0.514                         | 0.266                         | 1.0                             |                                  |
| 0.002| 0    | 5.0                         | 5.2                       | 74.26                  | 5.18                      | 0.176                         | 0.106                         | 4.32                            | 2.2                              |
| 0    | 0.002| 10.0                        | 2.1                       | 20.82                  | 2.05                      | 0.150                         | 0.143                         | 7.52                            | 4.1                              |
| 0.002| 0    | 10.0                        | 5.2                       | 20.97                  | 5.19                      | 0.088                         | 0.081                         | 2.67                            | 2.8                              |
| 0.002| 0    | 10.0                        | 5.2                       | 20.97                  | 5.19                      | 0.084                         | 0.030                         | 2.37                            | 2.7                              |

Note. The columns list (in order) metallicity; wind-driving efficiency; initial donor-star mass; initial orbital period; stellar age at RLOF; orbital period at ROLF; durations at which the X-ray luminosity exceeds $10^{39}$, $10^{40}$, and $10^{41}$ erg s$^{-1}$; and maximum X-ray luminosity.
toward the long orbital periods and short orbital periods, respectively. When $Z = 0.001$, the shift directions of the upper (long orbital periods) and lower (short orbital periods) parts of left boundaries with $L_X > 10^{40}$ erg s$^{-1}$ and $L_X > 10^{41}$ erg s$^{-1}$ are similar to those for $Z = 0.02$. It is clear that the irradiation-driven winds cannot readily affect the initial parameter of ULXs, whereas it shrinks the initial parameter space of IMBH binaries that evolve toward ULXs with high luminosity ($L_X > 10^{40}$ erg s$^{-1}$) and HLXs. Considering the irradiation effect, there are 220 and 223 grids within the contours with $L_X > 10^{40}$ erg s$^{-1}$ for $Z = 0.02$ and 0.001, respectively, while these two numbers increase to be 252 and 240 without the irradiation effect. Assuming that initial donor-star masses and initial orbital periods satisfy a uniform distribution, 58% (174 grids) and 65% (195 grids) of IMBH binaries can evolve toward HLXs when $Z = 0.02$ and 0.001, respectively. If the irradiation effect is not included, these two percentages...
respectively increase to be 72% (215 grids) and 70% (209 grids).

4. Discussion

IMBH X-ray binaries are broadly important in astrophysics in that (1) they are important candidates of ULXs and HLXs (Hopman et al. 2004; Li 2004; Portegies Zwart et al. 2004b; Patruno et al. 2006) and (2) some IMBH X-ray binaries with compact orbits are potential GW sources that would be visible to LISA, TianQin, and Taiji (Portegies Zwart et al. 2004b; Chen 2020).

Considering the irradiation effect, our simulations indicate that the initial parameter space of IMBH X-ray binaries evolving toward HLXs tends to shrink, especially for the donor stars with a metallicity of \( Z = 0.02 \). Meanwhile, the durations of the HLX stage shorten. In an X-ray and optical study, Sutton et al. (2012) found that the X-ray spectrum properties of eight ULX candidates are consistent with the sub-Eddington hard state, providing evidence of the existence of IMBHs with masses in the range of \( 10^3 - 10^4 M_\odot \). However, only two objects can be classified as HLX candidates in at least one observation (Sutton et al. 2012), implying a very small number of HLXs identified so far. The irradiation effect may be responsible for the phenomenon that most IMBH X-ray binaries do not readily appear as HLXs at any stage of their life.

It strongly depends on the X-ray luminosity whether the irradiation effect plays a key role in determining the evolution of X-ray binaries. Neglecting the irradiation effect, Li (2004) found that IMBH and stellar-mass BH X-ray binaries are similar in terms of their donor stars and binary orbits. After the Eddington accretion rate is included, the X-ray luminosities of IMBH X-ray binaries are approximately two orders of magnitude higher than those of stellar-mass BH X-ray binaries, yielding high loss rates of irradiation-driven winds and high rates of angular momentum loss. Therefore, the influence of the irradiation effect on IMBH X-ray binaries would obviously exceed that on stellar-mass BH X-ray binaries.

If the initial orbital periods are less than the bifurcation period, the IMBH X-ray binaries would evolve toward compact X-ray sources and be visible as continuous low-frequency GW sources (Chen 2020). For the fine-tuning of the initial orbital periods that are near the bifurcation period, the final products of IMBH X-ray binaries are detached IMBH binaries including a low-mass He WD (\( \sim 0.2 M_\odot \); see also Figure 4). With the inspiraling of the WD, the IMBH–WD binary will yield low-frequency GWs and appears as a LISA source. Once the WD penetrates the tidal radius of the IMBH, it will yield accretion-driven flares from the tidal disruption of the WD by the IMBH, which may account for gamma-ray burst GRB 060218 (Shcherbakov et al. 2013; Shen 2019) and two fast X-ray transients XT1 and XT2 in the Chandra Deep Field data (Peng et al. 2019). However, the influence of the irradiation effect on these processes can be ignored because their progenitors are normal X-ray sources.

If the initial donor-star masses are greater than 10 \( M_\odot \), IMBH X-ray binaries would evolve toward IMBH-NS binaries, which may be discovered by deeper surveys or next-generation radio telescopes such as the Square Kilometer Array (Patruno et al. 2005). About 9.5% of IMBH binaries are disrupted in their supernova explosions, which results in an isolated IMBH and an isolated radio pulsar (Portegies Zwart 2010). Of the surviving IMBH-NS systems, only 0.6% merge to appear as GW sources because most systems should have relatively long orbital periods (of at least 10 days; Hopman & Portegies Zwart 2005). Because the irradiation effect would efficiently drive an angular momentum loss for ULXs, producing relatively compact orbits, the fraction of disrupted IMBH binaries and IMBH-NS GW sources should decrease and increase, respectively.

Observational constraints proposed a space density for globular clusters as \( n_{GC} \approx 4 \text{ Mpc}^{-3} \) (Brodie & Strader 2006; Ramirez-Ruiz & Rosswog 2009). Hopman et al. (2004) found that IMBHs capture companions and then successfully circularize at a rate \( \Gamma \approx 5 \times 10^{-8} \text{ yr}^{-1} \) in globular clusters. Using the initial mass function, we can roughly estimate the probability that an IMBH captures a donor star with a mass in the range from \( i \) to \( j(M_\odot) \) as

\[
P_{i,j} = \int_{i}^{j} a \xi(M) dM,
\]

where \( \xi(M) dM \) is the probability that the mass of a star is in the range from \( M \) to \( M + dM \) (Kroupa et al. 1993). Assuming that the masses of stars in globular clusters are in the range of 1–20 \( M_\odot \), i.e., \( P_{c,1-20} = 1 \), we have \( P_{c,1-3} = 0.85 \) and \( P_{c,4-20} = 0.15 \). Assuming that the initial orbital periods of IMBH binaries obey a uniform distribution, the probability that the IMBH binaries with a donor-star mass in the range from \( i \) to \( j(M_\odot) \) appear as ULXs can be approximately estimated as

\[
P_{ULX,1-3} = 0.24 \quad \text{and} \quad P_{ULX,4-20} = 0.98
\]

for \( Z = 0.02 \) and when \( f = 0.01 \), and \( P_{ULX,1-3} = 0.44 \) and \( P_{ULX,4-20} = 0.89 \) for \( Z = 0.01 \) and \( f = 0.002 \) (where the probabilities are calculated by counting the grid numbers within the contours). Therefore, the estimated observation rate of ULXs in the globular clusters (taking \( Z = 0.02 \)) is roughly

\[
n_{GC,ULX} = n_{GC} \Gamma (P_{c,1-3} P_{ULX,1-3} + P_{c,4-20} P_{ULX,4-20}) 
\approx 70 \text{ Gpc}^{-3} \text{yr}^{-1}.
\]

According to the results of Section 3.3, the irradiation effect cannot influence the observation rate of ULXs in globular clusters. However, the estimated observation rate of HLXs would obviously decline if the irradiation effect were included.

5. Summary

As the transitional population between the stellar-mass BH and supermassive BH, IMBHs have generally been thought to reside in globular clusters, young dense clusters, and dwarf galaxies (Gürkan et al. 2004; Portegies Zwart et al. 2004a; Baumgardt 2017). In young dense clusters, main-sequence stars could spiral into IMBHs via exchange encounters or tidal capture and then feed material to the IMBHs via the Roche lobe overflow after the orbits are circularized (Hopman et al. 2004). Considering irradiation-driven winds produced at the surface of the donor star by strong X-ray flux from the accretion disk around the IMBH, we modeled the evolution of a large number of IMBH X-ray binaries. Our main conclusions are as follows:

1. The effect of the irradiation process with a low wind-driving efficiency \( (f = 0.001 \text{ for } Z = 0.02, \text{ and } f = 0.0002 \text{ for } Z = 0.001) \) on the X-ray luminosities of IMBH X-ray binaries can be ignored.

2. A relatively high wind-driving efficiency \( (f = 0.01 \text{ for } Z = 0.02, \text{ and } f = 0.002 \text{ for } Z = 0.001) \) obviously shortens the duration of the ULX stage of IMBH X-ray binaries with an
intermediate-mass donor star. However, this effect is very slight for high-mass donor stars. When $Z = 0.02$, the irradiation effect shortens the durations of $\Delta t_{40}$ by a factor at least 2, while this effect is not obvious for the donor stars with $Z = 0.001$.

3. Irradiation-driven winds play an important role in determining the orbital evolution of IMBH X-ray binaries. Because the irradiation-driven winds are ejected from the vicinity of the donor star, the rate of angular momentum loss is four orders of magnitude higher than that of isotropic winds induced by the super-Eddington accretion for the same mass-loss rate. Therefore, the final orbital periods of IMBH X-ray binaries are obviously shorter than those without the irradiation effect.

4. The irradiation effect cannot affect the initial parameter space of IMBH binaries that evolve toward ULXs, while it obviously shrinks those evolving toward ULXs with high luminosity and HLXs. Taking $f = 0.01$ $(Z = 0.02)$ and 0.002 $(Z = 0.001)$, 58% and 65% of IMBH binaries with a metallicity $Z = 0.02$ and 0.001 on the initial orbital period versus initial donor-star mass parameter space have an opportunity to evolve toward HLXs, respectively. If the irradiation effect is not included, these two fractions increase to 72% and 70%.

5. A low donor-star mass $(1-2 M_\odot)$ or short orbital period $(\sim 1-2$ days) tends to give rise to the emergence of normal X-ray sources in our parameter space, there exists an ultrasmall fraction $(\sim 1\%)$ of IMBH X-ray binaries with initial orbital periods shorter than the bifurcation period, some of which would evolve toward compact X-ray sources. None of these compact IMBH X-ray binaries can appear as ULXs, while they have an opportunity to be visible as low-frequency GW sources (Portegies Zwart et al. 2004b; Chen 2020). The influence of the irradiation effect on the evolution of these normal X-ray sources can be ignored owing to the low loss rates of irradiation-driven winds.

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