Compact Intermediate-mass Black Hole X-Ray Binaries: Potential LISA Sources?

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Abstract

The scientific aim of the space gravitational-wave (GW) detector Laser Interferometer Space Antenna (LISA) that was scheduled to launch in the early 2030s is to detect the low-frequency GW signals in the Galaxy. Its main candidate GW sources are compact binaries of white dwarfs and neutron stars. In this work, we examine whether compact intermediate-mass black hole (IMBH) X-ray binaries could be potential LISA sources. Our simulations indicate that an IMBH binary with a 1000 $M_\odot$ IMBH and a 3 $M_\odot$ donor star in an initial orbital period near the so-called bifurcation period of 0.77 day could evolve into an ultra-compact X-ray binary, which will emit GW signals with a maximum frequency of 2.5 mHz. According to the evolutionary tracks of characteristic strain, IMBH X-ray binaries with the initial donor-star masses of 1–3 $M_\odot$ and the initial orbital periods slightly less than the bifurcation periods will be detectable by the LISA in a distance of 15 kpc. Assuming each of 60 Galactic globular clusters hosts a 1000 $M_\odot$ IMBH, the maximum number of compact IMBH X-ray binaries that LISA will detect in the Galaxy should be less than ten. Therefore, the detectability of compact IMBH X-ray binaries by the LISA is not optimistic.

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

1. Introduction

It marked the start of observational gravitational-wave (GW) astronomy that the first high-frequency GW signals from the double black hole merger event GW150914 in the distant galaxy (Abbott et al. 2016) had been detected by the Advanced LIGO detectors (Aasi et al. 2015). In particular, the detection of the double neutron star coalescence GW170817 was a milestone in opening multi-messenger astronomy (Abbott et al. 2017).

A space GW detector Laser Interferometer Space Antenna (LISA) sponsored by the European Space Agency is scheduled to launch in the early 2030s (Amaro-Seoane et al. 2017). The scientific aim of the LISA will be to detect the low-frequency GW signals, and its sensitive frequencies are in a band between 0.1 mHz to 0.1 Hz, corresponding to orbital periods in the range of 20 s to 5 hr of binary systems (van der Sluys 2011). In the Milky Way, there exist a number of classes of binary systems that the LISA would and should detect (Nelemans et al. 2001; van der Sluys 2011). These potential LISA sources can be divided into the following two classes: the first one is detached binaries, including double white dwarfs, white dwarf—neutron star binaries, and double neutron stars; the second one is interacting binaries, i.e., cataclysmic variables (CVs), AM CVn stars, and ultra-compact X-ray binaries.

Both population synthesis simulations and observation calibrations show that the expected number of double white dwarfs can reach several hundred million in the Galaxy (Nelemans et al. 2001; Liu et al. 2010; Ruiter et al. 2010; Yu & Jeffery 2010). Based on a semi-analytic model, some works investigated the chirp of the emitting GW signals from double white dwarfs with the mass transfer (Hils & Bender 2000; Kaplan et al. 2012; Kremer et al. 2017), and double neutron stars (Yu & Jeffery 2015). Recently, Tauris (2018) performed a systematic work on the GW radiation of neutron star + white dwarf binaries, and found that ultra-compact X-ray binaries at a distance of 15 kpc can be detected by the LISA.

Recently, the existence of intermediate-mass black holes (IMBHs) in globular clusters was supported by a growing number of observational and theoretical evidences (Portegies Zwart et al. 2004a). Gair et al. (2011) predicted that the Einstein Telescope would detect thousands of IMBH binary mergers per year in the future. Fragione et al. (2018) proposed that LISA and the Einstein telescope would be the best instruments detecting the merger events originating from the inspirals of IMBH stellar-mass black hole systems. Mandel et al. (2008) suggested that the inspirals of stellar-mass compact objects into IMBHs in globular clusters can be detected by the advanced GW detectors. Most recently, Jani et al. (2020) showed that the inspiral, merger, and ringdown of IMBH binaries will be detected by the LIGO and the LISA in multiband observations. However, the inspiral or merger of double IMBHs should be electromagnetically quiet. Compact IMBH X-ray binaries with stable mass transfer should be intriguing GW sources, which give us a chance to pursue full multi-messenger investigations. The tidal capture or exchange encounters in young dense star clusters could result in main-sequence stars spiraling into and circularizing around some IMBHs (Hopman et al. 2004). For example, the ultra-luminous X-ray source (ULX) in the young cluster MGG-11 of M82 may be an accreting IMBH from a captured donor star (Hopman et al. 2004). Because of the massive masses of IMBHs, it is possible for IMBH binaries to evolve into compact IMBH X-ray binaries via very strong gravitational radiation. Portegies Zwart et al. (2004b) found that an IMBH X-ray binary with a donor star of 2 $M_\odot$ and an initial orbital period of 0.5 day is visible as GW sources in its whole lifetime. In this work, we attempt to examine whether compact IMBH X-ray binaries could be potential LISA sources.

2. Evolution of Compact IMBH X-Ray Binaries

To obtain compact IMBH X-ray binaries, we calculate the evolution of some IMBH binaries. The simulation employs a MESAbinary update version (r12115) in the Modules for
Experiments in Stellar Astrophysics code (MESA; Paxton et al. 2015). The evolutionary beginning is a binary system consisting of an IMBH (with a mass of $M_{\text{bh}}$) and a main-sequence companion star (with a mass of $M_d$) in a circular orbit. The IMBH is assumed to be a point mass, and the chemical composition of the companion star is $X = 0.7$, $Y = 0.28$, $Z = 0.02$. The loss of orbital-angular momentum plays a key role in influencing the evolution of IMBH binaries. Three loss mechanisms of angular momentum by gravitational radiation, magnetic braking (Rappaport et al. 1983), and mass loss are included. If the donor star develops a convective envelope and possesses a radiative core, magnetic braking will turn on, and magnetic braking is no longer active. During the mass transfer, the accretion rate onto the IMBH is limited to the Eddington accretion rate (Podsiadlowski et al. 2003). The mass loss from the vicinity of the IMBH is thought to carry away the specific orbital-angular momentum of the IMBH, while the donor-star winds carry away the specific orbital-angular momentum of the donor star. We run the MESA code until the donor-star radius is less than the tidal radius ($R_f = (M_{\text{bh}}/M_d)^{1/3}R_d$, here $R_d$ is the donor-star radius) of the IMBH (Kochanek 1992), or the time step is less than the minimum time-step limit, or the stellar age is greater than the Hubble timescale.

To examine whether compact IMBH X-ray binaries can be formed, we calculate the evolution of a large numbers of IMBH binaries with different initial orbital periods. The initial masses of the IMBHs and the donor stars are assumed to be $1000 M_\odot$ and $3 M_\odot$, respectively. In Figure 1, we plot the evolutionary tracks of four IMBH binaries in the $P_{\text{orb}}-M_d$ plane, where $P_{\text{orb}}$ is the orbital period. It seems that there also exists a so-called bifurcation period like neutron star low-mass X-ray binaries (van der Sluys et al. 2005a, 2005b). In principle, the bifurcation period is related to the angular momentum loss mechanisms (Plyryer & Savonije 1988, 1989; Ergma et al. 1998; Podsiadlowski et al. 2002; Ma & Li 2009). Based on the angular momentum loss mechanisms adopted in this work, the bifurcation period of an IMBH binary with a donor star of $M_d = 3 M_\odot$ is 0.77 day. Our simulated results come to the same the conclusion given by Chen & Podsiadlowski (2016). IMBH binaries with initial periods near the bifurcation period tend to form more compact IMBH X-ray binaries. For example, when the initial period is $P_{\text{orb},i} = 0.77$ day, the IMBH binary will evolve into a compact IMBH X-ray binary with orbital period $P_{\text{orb}} = 14$ minutes; when $P_{\text{orb},i} = 0.75$ and 0.65 day, the minimum orbital periods will be 1.7 and 2.6 hr. During the mass transfer, the angular momentum loss is dominated by the gravitational radiation, which is at least 1–2 orders of magnitude higher than the magnetic braking. For an initial orbital period of 0.78 day greater than the bifurcation period, the IMBH binary will evolve into an IMBH X-ray binary with wide orbit (see also Figure 1). It is possible to evolve into compact ($P_{\text{orb}} \lesssim 2$ hr) IMBH X-ray binaries for IMBH binaries with initial orbital periods less than the bifurcation period.

Figure 2 shows that the evolutionary track of the X-ray luminosity for an IMBH X-ray binary with $P_{\text{orb},i} = 0.77$ day. We compute the X-ray luminosity by $L_X = 0.1 M_{\text{bh}} c^2$, here $M_{\text{bh}}$ is the accretion rate, $c$ is the light velocity in vacuo. After 34.5 Myr nuclear evolution, the donor star overflows its Roche lobe, and transfers its H-rich material to the IMBH. In the most life, the IMBH X-ray binary appears as a normal X-ray source, and the X-ray luminosity is in the range of $\sim 10^{36}$ to $10^{37}$ erg s$^{-1}$. At the final stage, the X-ray luminosity sharply increases due to the rapid shrinkage of the orbit. When the age of the donor star is 3672.65 Myr, the X-ray luminosity exceeds $10^{39}$ erg s$^{-1}$, and the IMBH X-ray binary becomes a ULX source.

3. Detectability of LISA

Figure 3 shows the evolution of the frequency derivative $\dot{f}$ as a function of the frequency $f$ ($f = 2/P_{\text{orb}}$) of GW signals for the evolutionary final stage of the IMBH X-ray binary plotted in Figure 2. It is clear that the maximum of $\dot{f}$ is close to the maximum of $f$. When $f_{\text{max}} = 2.5$ mHz, the maximum frequency derivative $\dot{f}_{\text{max}} \approx 7.0 \times 10^{-16}$ Hz s$^{-1}$. For a detection duration $T = 4$ yr, the maximum frequency change is $\Delta f_{\text{max}} = 9.0 \times 10^{-8}$ Hz. Therefore, the GW signals emitted by such an IMBH X-ray binary can be thought of as being monochromatic. By accumulating the power in the signal over cycles of $T f$ for an observation duration $T$, the characteristic strain of GW can be

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Evolutionary tracks of IMBH binaries with a donor-star mass of $3.0 M_\odot$ and different initial orbital periods in the $P_{\text{orb}}$-$M_d$ diagram. The solid, dashed, dotted, and dashed–dotted curves correspond to the initial orbital periods of 0.77, 0.75, 0.65, and 0.78 days, respectively.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Calculated X-ray luminosity as a function of the stellar age for IMBH X-ray binary with $M_{\text{bh}} = 1000 M_\odot$, $M_d = 3 M_\odot$, and $P_{\text{orb},i} = 0.77$ day. The cross represents the moment that IMBH X-ray binary appears as ULX.
15 kpc, curve originates from a good analytic model in the frequency diagram. The LISA sensitivity curve by the black binaries in the characteristic strain amplitude versus GW frequency given by the numerical calculation. When the chirp mass $M_{\text{chirp}}$ and the chirp mass $d_L$ luminosity distance where $T = 4$ yr, we have

$$h_{\text{c}} \approx 2.5 \times 10^{-20}\left(\frac{f}{1 \text{ mHz}}\right)^{7/6} \left(\frac{\mathcal{M}}{1 \, M_\odot}\right)^{5/3} \left(\frac{15 \text{ kpc}}{d_L}\right),$$

and the chirp mass

$$\mathcal{M} = \frac{c^2}{G} \left(\frac{5\pi^{-8/3}}{96} f^{-11/3} \dot{f}\right)^{3/5}.$$  

An accurate measurement for the frequency derivative $\dot{f}$ by the LISA requires a very large signal-to-noise ratio ($S/N$). The resolution on the frequency derivative $\dot{f}$ can be estimated to be (Tauris 2018)

$$\dot{f}_{\text{min}} \approx 2.5 \times 10^{-18} \left(\frac{100}{S/N}\right) \left(\frac{4 \text{ yr}}{T}\right)^2 \text{ Hz s}^{-1}. $$

For the IMBH X-ray binary in Figure 3, $\dot{f} = 2.5 \times 10^{-18} \text{ Hz s}^{-1}$ when $f = 0.4 \text{ mHz}$. This implies that the LISA will be able to detect the chirp signals from such a system when $f > 0.4 \text{ mHz}$ for an S/N above 100.

Figure 4 shows the evolutionary tracks of five IMBH X-ray binaries in the characteristic strain amplitude versus GW frequency diagram. The LISA sensitivity curve by the black curve originates from a good analytic model (see also Equation (13) in Robson et al. 2019), while the red curve shows the results given by the numerical calculation. When $d_L = 15 \text{ kpc}$, five IMBH X-ray binaries with an initial orbital period equaling the bifurcation period can penetrate the LISA sensitivity curve, and appear as potential LISA sources. Even if $d_L = 1 \text{ Mpc}$, IMBH X-ray binaries with donor-star masses of 3.0, 1.5, and 1.0 $M_\odot$ are still visible as the LISA sources.

To obtain the initial parameter space of the progenitors of IMBH X-ray binaries that can be detected by the LISA, we have simulated the evolution of a great number of IMBH binaries in the $P_{\text{orb}}$-$M_{\text{bin}}$ plane. In Figure 5, the IMBH binaries are denoted by the filled circles if their descendants will be visible by the LISA for $d_L = 15 \text{ kpc}$. The solid curve shows the bifurcation periods of IMBH binaries for different donor-star masses. All systems above this curve will evolve into IMBH X-ray binaries with a long orbital period (including the cases $M_d = 3.5 \, M_\odot$, and $P_{\text{orb}} \geq 0.7 \text{ day}$), which cannot enter the sensitivity frequency scope of the LISA. The bifurcation periods display a tendency, in which a larger donor-star mass corresponds to a smaller bifurcation period. It is clear that the progenitors of LISA sources tend to have an orbital period slightly lower than the bifurcation period. IMBH binaries with initial orbital periods obviously lower than the bifurcation period are difficult to evolve into compact orbits that the LISA can detect.

In Table 1, we summarize some evolutionary quantities of IMBH binaries with their respective bifurcation periods for different initial donor-star masses. All IMBH binaries with initial orbital periods equal to the bifurcation periods can evolve into ultra-compact IMBH X-ray binaries with orbital periods less than 34 minutes (which corresponds to a GW frequency of 1 mHz). The initial GW frequency at which these sources are visible by the LISA is $0.22-0.23 \text{ mHz}$. The timescales of IMBH X-ray binaries as LISA sources are roughly 7-54 Myr, while they appear as luminous X-ray source ($L_X > 10^{38} \text{ erg s}^{-1}$) only last $\sim 0.02-2.0 \text{ Myr}$. In principle, it is difficult for compact IMBH X-ray binaries to become ULXs. When $M_d = 2.0$, and $2.5 \, M_\odot$, the donor stars evolve into plant-like mass objects that are absent in surface hydrogen content, just like the donor star of black widow pulsar PSR J1311–3430 (Pletsch et al. 2012). It was already noticed that the initial orbital periods should be less than and near the bifurcation period in order to form a donor star like PSR J1311–3430 (Benvenuto et al. 2013).

We next estimate the maximum number of compact IMBH X-ray binaries that LISA will detect. It is generally thought that IMBHs reside in globular clusters, young dense clusters, and dwarf galaxies. For young dense clusters, it is too young to produce such compact IMBH X-ray binaries. In the Galaxy, there exist 137 globular clusters. However, Holley-Bockelmann et al. (2008) found that only 60 Galactic globular clusters are able to retain IMBHs with an initial mass of $1000 \, M_\odot$. Assuming the number of IMBHs $N_{\text{IMBH}} = 60$, the number of IMBH X-ray binaries appearing as LISA sources can be estimated as

$$N_{\text{IMBH-LISA}} = N_{\text{IMBH}} \Gamma_{\text{PGC-LISA}} / t_{\text{ev}}.$$  

According to the simulation given by Hopman et al. (2004), the rate that IMBHs capture companions is $\Gamma \sim 5 \times 10^{-8}$. Assuming that initial companion masses $(1-3 \, M_\odot)$ and initial orbital periods $(0.5-3.5 \text{ days})$ obey a uniform distribution, the probability that the IMBH binaries satisfy the parameter space of the progenitors of potential LISA sources $P \sim 0.1$ should be an optimistic estimation. The age $t_{\text{GC}}$ of the globular clusters is approximately two times as long as the evolutionary timescale $t_{\text{ev}}$ of IMBH X-ray binaries. The timescale that compact IMBH
X-ray binaries are visible as LISA sources $t_{\text{LISA}} \sim 10$ Myr. Therefore, the maximum number that IMBH X-ray binaries appear as LISA source in the Galaxy should be less than ten. This number is obviously smaller than those of ultra-compact X-ray binaries ($\gtrsim 100$, Tauris 2018), AM CVn, and double white dwarf systems (Nelemans et al. 2001).

4. Discussion and Summary

Detectability of inspirals of stellar-mass compact objects into IMBHs (Mandel et al. 2008) or double IMBHs (Amaro-Seoane & Freitag 2006; Veitch et al. 2015), and merging of IMBHs and compact objects (Mapelli et al. 2010; Haster et al. 2016) or double IMBHs (Matsubayashi et al. 2004; Abadie et al. 2012; Mazzolo et al. 2014) as GW sources were extensively studied. However, compact IMBH X-ray binaries with stable mass transfer present a chance to pursue full multi-messenger investigation, providing much valuable information about stellar and binary evolution. In this work, we diagnose whether IMBH X-ray binaries can be intriguing GW sources that the LISA will detect. Employing the MESA code, we simulate the evolution of a great number of IMBH binaries, and find that the systems with initial orbital periods lower than the bifurcation period can evolve into tight orbits due to the strong gravitational radiation. When $M_{\text{bh}} = 1000 M_\odot$, $M_\text{d} = 1.0$–$3.0 M_\odot$, all IMBH binaries with initial orbital periods equaling to the bifurcation periods can evolve into compact IMBH X-ray binaries, which can easily be detected by the LISA at a distance of $d_L = 15$ kpc. In particular, several compact IMBH X-ray binaries will still be visible as LISA sources even if it is at a distance of $d_L = 1$ Mpc (see also Figure 4).

We also explore the parameter space of the progenitors of IMBH X-ray binaries as potential LISA sources. For initial donor-star masses in the range of 1.0–$3.0 M_\odot$, and initial orbital periods in the range of 0.7–3.2 days (depending on the donor-star masses), the corresponding IMBH binaries can evolve into promising LISA sources. Some IMBH binaries with shorter orbital periods can evolve into compact IMBH X-ray binaries, however, they will not be detectable for the LISA due to the low characteristic strain. After inspirals of normal stars into IMBHs and circulation, orbital-angular momentum conservation predicted an orbital separation $a \sim (4–5)(M_{\text{bh}}/M_\odot)^{1/3}R_d$ (Hopman et al. 2004). This indicates that the initial orbital
Note. The columns list (in order): the initial donor-star mass, bifurcation period, orbital period, central H abundance at the beginning of Roche lobe overflow, final surface H abundance, minimum orbital period, final donor-star mass, duration that the IMBH X-ray binary is visible as a LISA source, initial GW frequency appearing as a LISA source, duration that the IMBH X-ray binary appears as ULX, and duration that the IMBH X-ray binary appears as a luminous source ($L_\odot > 10^{38}$ erg s$^{-1}$).

**Selected Evolutionary Properties for IMBH Binaries with Their Respective Bifurcation Periods for Different Initial Donor-star Masses**

| $M_{\odot}$ ($M_{\odot}$) | $P_{\text{inf}}$ (days) | $P_{\text{orb}}$ (days) | $X_{c,\text{chirp}}$ | $X_{\text{orb},\text{min}}$ | $P_{\text{orb}}$ (min) | $M_{\text{max}}$ ($M_{\odot}$) | $\delta t_{\text{LISA}}$ (Myr) | $\delta t_{\text{LX}}$ (Myr) | $\delta t_{\text{ULX}}$ (Myr) |
|-------------------------|------------------------|------------------------|----------------------|------------------------|------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 1.0                     | 3.23                   | 0.60                   | 1.8e−11              | 0.17                   | 14                     | 0.12                     | 8.4                      | 0.23                     | 0.02                     | 0.13                     |
| 1.5                     | 1.07                   | 0.19                   | 0.90                 | 0.00                   | 11                     | 0.13                     | 6.9                      | 0.22                     | 0.006                    | 0.02                     |
| 2.0                     | 1.41                   | 0.43                   | 3.9e−5               | 0.43                   | 34                     | 0.0009                   | 19.2                     | 0.22                     | 0                        | 1.8                      |
| 2.5                     | 1.05                   | 0.56                   | 2.6e−13              | 0.43                   | 21                     | 0.0016                   | 54.9                     | 0.23                     | 0                        | 1.9                      |
| 3.0                     | 0.77                   | 0.62                   | 0.07                 | 14                     | 0.11                   | 9.6                      | 0.23                     | 0.03                     | 0.3                      |

periods of IMBH binaries are approximately 2–4 days (Li 2004). Therefore, the parameter space that we predict is reasonable, and the relevant IMBH binaries could form via tidal (Hopman et al. 2004) or dynamical capture (Baumgardt et al. 2004; however, dynamical capture events tend to produce IMBH binaries with orbital periods of 100–1000 days) in globular clusters. Similar to the conclusion of Portegies Zwart et al. (2004b), it is impossible for IMBH X-ray binaries with massive donor stars of $\lesssim 4 M_{\odot}$ to reach the sensitive frequency scope of the LISA.

Our simulation indicates that compact IMBH X-ray binaries in most lifetimes appear as normal X-ray sources, not ULXs. At present, compact IMBH X-ray binaries are rare in observations, which should arise from the selection effect. Compared with stellar-mass black holes, IMBHs have a sole merit in forming compact binary systems. Because the loss rate of angular momentum by the gravitational radiation $\dot{J}_{\text{gr}} \propto M_{\odot}^{5/2}$, $\dot{J}_{\text{gr}}$ of IMBH (with a mass of 1000 $M_{\odot}$) is five orders of magnitude higher than the stellar-mass black hole (with a mass of 10 $M_{\odot}$). Therefore, IMBH binaries can easily evolve into compact orbits, without invoking magnetic braking of Ap/Bp stars (Justham et al. 2006) or circumbinary disk (Chen & Li 2006, 2015; Chen & Podsiadlowski 2019) like stellar-mass black hole X-ray binaries. On the other hand, the characteristic strain of GW $h_c \propto \lambda^{5/3}$, the chirp signals from IMBH X-ray binaries will be easily detected by the LISA. As a result, we propose that the detection of GW signal for some luminous X-ray sources with tight orbits could distinguish the nature of the accreting objects (IMBH or stellar-mass black hole).

Compared with ultra-compact X-ray binaries, AM CVn stars, and detached double white dwarf systems, the probability that IMBH X-ray binaries will be detected by the LISA is not optimistic. First, IMBHs are very rare, and they may only exist in globular clusters and young dense clusters. Second, the rate at which IMBHs accompany main-sequence stars via tidal or dynamical capture is very low. Third, the initial parameter space of compact IMBH X-ray binaries that LISA will detect is very narrow. Assuming each of 60 Galactic globular clusters hosts a 1000 $M_{\odot}$ IMBH, the optimistic estimation for the number of IMBH X-ray binaries that LISA will detect in the Galaxy should be less than ten. Furthermore, it seems that the maximum detection distance for IMBH X-ray binaries can reach 1 Mpc, while the GW signals from double white dwarf systems are most likely dominant in the relevant area due to the initial mass function. Therefore, the extragalactic IMBH X-ray binaries are not expected to be detectable by the LISA. As a result, the detection probability of IMBH X-ray binaries by the LISA is not optimistic, although they provide an opportunity of multi-messenger investigation. We expect that the observations of the LISA can confirm or rule out our idea in the future.

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