Formation rate of LB-1-like systems through dynamical interactions

Ataru TANIKAWA¹, Tomoya KINUGAWA², Jun KUMAMOTO² and Michiko S. FUJII,²

¹Department of Earth Science and Astronomy, College of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan
²Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

∗E-mail: tanikawa@ea.c.u-tokyo.ac.jp

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Abstract

We estimate formation rates of LB-1-like systems through dynamical interactions in the framework of the theory of stellar evolution before the discovery of the LB-1 system. The LB-1 system contains $\sim 70 M_\odot$ black hole (BH), so-called pair instability (PI)-gap BH, and B-type star with solar metallicity, and has nearly zero eccentricity. The most efficient formation mechanism is as follows. In an open cluster, a naked helium (He) star (with $\sim 20 M_\odot$) collides with a heavy main-sequence (MS) star (with $\sim 50 M_\odot$) which has a B-type companion. The collision results in a binary consisting of the collision product and B-type star with a high eccentricity. The binary can be circularized through the dynamical tide with radiative damping of the collision-product envelope. Finally, the collision product collapses to a PI-gap BH, avoiding pulsational pair instability and pair instability supernovae because its He core is as massive as the pre-colliding naked He star. We find that the number of LB-1-like systems in the Milky Way galaxy is $\sim 0.1 (\rho_{oc}/10^4 M_\odot pc^{-3})$, where $\rho_{oc}$ is the initial mass densities of open clusters. If we take into account LB-1-like systems with O-type companion stars, the number increases to $\sim 0.3 (\rho_{oc}/10^4 M_\odot pc^{-3})$. This mechanism can form LB-1-like systems at least 100 times more efficiently than the other mechanisms: captures of B-type stars by PI-gap BHs, stellar collisions between other type stars, and stellar mergers in hierarchical triple systems.

Key words: stars: individual (LB-1) — stars: black holes — binaries: close — open clusters and associations: general

1 Introduction

Stellar-mass black holes (BHs) are the end state of massive stars. They have long been observed only as X-ray binaries (Remillard & McClintock 2006, for review). In the last few years, however, gravitational wave radiations have been successfully detected from mergers of binary BHs (BH-BHs) (Abbott et al. 2016b, 2016a, 2017a, 2017c, 2017b, 2019b; Venumadhav et al. 2019; Zackay et al. 2019). Since these achievements accelerate BH explorations, spectroscopic observations have recently discovered BHs in wide binaries, i.e. those without interactions with their luminous companion stars (Giesers et al. 2018; Thompson et al. 2019; Liu et al. 2019). These discoveries are rapidly putting forward our understanding of BHs.

The LB-1 system, a binary composed of a BH and luminous companion star, has been discovered by Liu et al. (2019) using...
spectroscopic observations. The BH mass of the LB-1 system was estimated to be $\sim 70M_\odot$, and the luminous companion has solar (or supersolar) metallicity. The estimated binary eccentricity $\sim 0.03$, nearly zero. The formation of LB-1-like system is quite challenging for the currently known theories of single stellar evolution for the following reasons. Massive stars evolve to naked helium (He) stars due to strong stellar-wind mass-loss under solar metallicity environment, and as a result they leave at most $20M_\odot$ BHs (e.g. Vink et al. 2001; Belczynski et al. 2010). Even if stellar wind does not work well for some reason, massive stars with large He cores should undergo pair instability supernovae (PISNe) (Bond et al. 1984; Fryer et al. 2001; Chatzopoulos & Wheeler 2012) or pulsational pair instability supernovae (PPISNe) (Heger & Woosley 2002; Woosley et al. 2007; Leung et al. 2019). These effects limit BH masses to less than $\sim 50M_\odot$ under any metallicity environments (Belczynski et al. 2016b). Massive stars with a mass of $> \sim 300M_\odot$ first overcome PPISN/PISN effects, and directly collapse to BHs with little mass loss (Heger & Woosley 2002). Therefore, there should be no BH in a mass range from $\sim 50M_\odot$ to $\sim 300M_\odot$ if we consider single stellar evolution theories, and this mass range is called pair instability (PI) gap (Abbott et al. 2019a). In spite of these theoretical predictions, the LB-1 system has a BH with $\sim 70M_\odot$. In response to this discovery, several studies have reconsidered massive star evolution; they have reduced effects of stellar wind mass loss (e.g. Belczynski et al. 2019; Groh et al. 2019). Note that several studies have pointed out possibilities that Liu et al. (2019) may misinterpret their observational results (Eldridge et al. 2019; Abdul-Masih et al. 2019; El-Badry & Quataert 2019).

BH-BH mergers to form $\sim 70M_\odot$ BH were detected by gravitational wave (GW) detectors such as LIGO and Virgo (e.g. Abbott et al. 2016b, 2019b). If an inner BH-BH of a hierarchical triple system with a B-type third star merged, LB-1-like systems seem to be easily formed. However, this process would leave a LB-1-like system with a high eccentricity (hereafter, eccentric LB-1-like system), since the merged BH receives a kick with a velocity of $\geq 100$ km s$^{-1}$ due to the asymmetric GW radiation of the BH-BH merger (e.g. Berti et al. 2007; Campanelli et al. 2007; Lousto et al. 2010). This binary could be circularized by tidal interaction, but the time scale is estimated to exceed the Hubble time (Liu et al. 2019). If the $70M_\odot$ BH of LB-1 system is a BH-BH, we can avoid such a high kick velocity, but several studies have already ruled out this possibility (Liu et al. 2019; Shen et al. 2019).

Another scenario is capturing a B-type star after a BH-BH merger. If two BHs merge in a globular cluster, the merged BH can be retained in the globular cluster (Rodriguez et al. 2019). The merged BH could capture a B-type star through a binary-single encounter. However, such an encounter should also form a binary with a large eccentricity because the eccentricity of dynamically formed binaries has a thermal distribution (Heggie 1975).

In this paper, we assess a formation mechanism of LB-1-like systems in open clusters. Some recent studies have suggested that open clusters are one of probable formation sites of BH binaries (e.g. Kumamoto et al. 2019; Di Carlo et al. 2019a). Here, we do not assume the reduction of stellar-wind mass-loss, but dynamical formation mechanisms. The formation mechanism we propose includes...
in this paper is as follows (see also Figure 1). We consider a binary-star system with heavy main-sequence (MS) star with \( \sim 50 M_\odot \) and B-type star with \( \sim 8 M_\odot \), and a single naked He star with \( \sim 20 M_\odot \) in an open cluster. They form a LB-1-like system through the following four processes. (The numbers of these processes correspond to those in Figure 1.)

1. The binary and naked He star experience a close binary-single encounter. During this close encounter, the naked He star collides with the heavy MS star.

2. This collision forms a He star with a massive hydrogen (H) envelope. The collision product and B-type star compose a new binary. This binary has a finite eccentricity due to the collision.

3. The envelope of the collision product exerts tidal friction on the binary motion. Then, the binary orbit is circularized.

4. The collision product directly collapses to a PI-gap BH with a mass of \( \sim 70 M_\odot \). Note that this collapse avoids PPISN and PISN, since the He core mass is \( \sim 20 M_\odot \).

This binary finally escapes from the open cluster due to the two-body relaxation process or due to a close encounter with another star before the collision product collapses to a PI-gap BH. The formation mechanism of PI-gap BHs via stellar collisions in open cluster have been suggested in Spera et al. (2019) and Di Carlo et al. (2019b). However, no quantitative estimation for the formation and circularization of binaries has been given yet.

The collision product and B-type star are always bound because this binary-single encounter has negative energy owing to small velocity dispersion (\( \sim 1 \text{ km s}^{-1} \)) in open clusters. Note that the collision never yields some additional energy, differently from collisions of two white dwarfs (Raskin et al. 2009; Rosswog et al. 2009; Lorén-Aguilar et al. 2010; Dong et al. 2015). Gaburov et al. (2010) have shown that binary-single encounters end up with mergers among three stars. However, pre-existing binaries in their simulations are relatively close: semi-major axes of several 10\( R_\odot \). On the other hand, we suppose pre-existing binaries with semi-major axes of 1 au. Thus, three stars do not necessarily merge in our cases. After the formation, these binaries would never keep staying in open clusters. They are frequently ejected from open clusters through close encounters (Fujii & Portegies Zwart 2011; Banerjee et al. 2012). We can estimate the separation between these binaries and their formation sites as \( \sim 1(v_{ej}/30\text{km s}^{-1})(T_B/40\text{Myr}) \text{ kpc} \), where \( v_{ej} \) is the ejection velocity of these binaries from open clusters, and \( T_B \) is the lifetime of B-type stars. Therefore, the current locations of these binaries are not necessarily close to open clusters.

The following is the structure of this paper. In section 2, we roughly count the formation rate of binaries consisting of the collision products and B-type stars in the Milky Way (MW) galaxy. We call these binaries “LB-1-like progenitors”. In section 3, we calculate circularization timescale of the progenitors, and estimate the number of LB-1-like systems in the MW galaxy. In section 4, we rule out any other scenarios related to dynamical interactions. In section 5, we summarize this paper.

## 2 Formation rate of LB-1-like progenitors

In this section, we estimate the formation rate of LB-1-like progenitors formed in open clusters in the MW galaxy, \( \dot{N}_{LB1,p} \). We first define \( \dot{N}_{LB1,p} \) as

\[
\dot{N}_{LB1,p} = \dot{N}_{PIgap}\frac{\Gamma_{nHe}}{\Gamma_{eHe}}
\]

where \( \dot{N}_{PIgap} \) is the formation rate of PI-gap BHs in all the MW open clusters, and \( \Gamma_{nHe} \) and \( \Gamma_{eHe} \) are collision rates between heavy MS and naked He stars, and between heavy MS and He stars with H envelopes (enveloped He stars, hereafter), respectively. PI-gap BHs do not always become members of LB-1-like systems. PI-gap progenitors should be formed through collisions between heavy MS and naked/enveloped He stars. However, our scenario works only for collision between heavy MS stars and naked He stars as described in section 4. Thus, we need the factor \( \Gamma_{nHe}/\Gamma_{eHe} \). We implicitly assume that LB-1-like progenitors are formed at the same time as when PI-gap progenitors are formed through collisions between naked He stars and heavy MS stars. Either of naked He stars and heavy MS stars should have B-type companions, since massive stars indicate multiplicities with a high probability (Sana et al. 2012).

We first estimate \( \dot{N}_{PIgap} \), which can be expressed as

\[
\dot{N}_{PIgap} = \dot{f}_{PIgap}\eta_{mZAMS}f_{oc}\dot{M}_{\text{MW}}
\]

where \( \dot{f}_{PIgap} \) is the number fraction of PI-gap BHs to an open clusters, \( \eta_{mZAMS} \) is the expected number of zero-age MS (ZAMS) stars heavier than a certain mass \( m_{c}(M_\odot) \) per stellar mass, \( f_{oc} \) is the mass fraction of stars formed in open clusters, and \( \dot{M}_{\text{MW}} \) is the star formation rate in the MW galaxy. If we choose appropriate \( m_{c} \), we find that \( \eta_{m_{c}}f_{oc}\dot{M}_{\text{MW}} \) is the BH formation rate in all the MW open clusters. Using the results of Di Carlo et al. (2019b), we obtain the formation rate as...
\[ \dot{N}_{\text{PI-gap}} \sim 2 \times 10^{-6} \left( \frac{f_{\text{PI-gap}}}{0.002} \right) \left( \frac{\rho_{\text{oc}}}{10^4 \text{M}_\odot \text{pc}^{-3}} \right) \left( \frac{\eta_0}{0.003 \text{M}_\odot^{-1}} \right) \left( \frac{f_{\text{oc}}}{0.2} \right) \left( \frac{\dot{M}_{\text{MW}}}{2 \text{M}_\odot \text{yr}^{-1}} \right) \text{[yr}^{-1}] \].

Di Carlo et al. (2019b) have shown that \( f_{\text{PI-gap}} = 0.002 \) for solar metallicity in open clusters with the initial mass densities \( \rho_{\text{oc}} \sim 10^4 \text{M}_\odot \text{pc}^{-3} \). Note that \( f_{\text{PI-gap}} \) should be proportional to \( \rho_{\text{oc}} \), since PI-gap BHs are formed through collisions between heavy MS and naked/enveloped He stars. We obtain from the SSE code (Hurley et al. 2000) that MS stars leave BHs when their masses are \( \geq 20 \text{M}_\odot \). Then, we find \( \eta_0 = 0.003 \text{M}_\odot^{-1} \), assuming stellar initial mass function (IMF) as the Kroupa IMF in the mass range from 0.08 \( \text{M}_\odot \) to 150 \( \text{M}_\odot \) (Kroupa 2001). We derive \( f_{\text{oc}} \) as follows. The total mass of open clusters with a mass of more than \( 10^4 \text{M}_\odot \) born within 100 Myr in 1 kpc from the sun is \( 5.3 \times 10^4 \text{M}_\odot \) (Piskunov et al. 2007). From this, we estimate that the current star formation rate density of stars born in open clusters is \( 5.3 \times 10^{-4} \text{M}_\odot \text{yr}^{-1} \text{kpc}^{-2} \). Since the star formation rate density at a Galactic radius of 8 kpc is estimated to be \( \sim 3 \times 10^{-3} \text{M}_\odot \text{yr}^{-1} \text{kpc}^{-2} \) (Missiroli et al. 2006), we estimate that \( f_{\text{oc}} \sim 0.18 \). The current total star-formation rate of the MW galaxy is \( \dot{M}_{\text{MW}} = 1.65 \pm 0.19 \text{M}_\odot \text{yr}^{-1} \) (Bland-Hawthorn & Gerhard 2016).

Before calculating \( \Gamma_{\text{nHe}}/\Gamma_{\text{eHe}} \), we give formulae for any rates of stellar collision/encounter between type-1 and type-2 stars, \( \Gamma \), such that

\[ \Gamma = N_1 n_2 \sigma_{12} v_{12}, \]

where \( N_1 \) is the number of type-1 stars, \( n_2 \) is the number density of type-2 stars, \( \sigma_{12} \) is the cross section of the collision/encounter, and \( v_{12} \) is the relative velocity of these stars. Note that type-1 and type-2 stars are interchangeable. The cross section can be written as

\[ \sigma_{12} = \pi R_{12}^2 \left( 1 + \frac{2GM_{12}}{R_{12}v_{12}^2} \right), \]

where \( G \) is the gravitational constant, \( M_{12} \) is the total mass of type-1 and type-2 stars, and \( R_{12} \) is critical separation between type-1 and type-2 stars below which these stars are considered to collide/encounter. Usually, the second term in the parentheses is dominant. Thus, we define the product of \( \sigma_{12} \) and \( v_{12} \) as a sweeping volume per unit time, \( V_{12} \):

\[ V_{12} \equiv \sigma_{12} v_{12} \sim 2\pi GM_{12} R_{12} v_{12}^{-1}. \]

Now, we can express \( \Gamma_{\text{nHe}}/\Gamma_{\text{eHe}} \) as

\[ \frac{\Gamma_{\text{nHe}}}{\Gamma_{\text{eHe}}} = \frac{N_1,\text{nHe} n_2,\text{nHe} M_{12,\text{nHe}} v_{12,\text{nHe}}}{N_1,\text{eHe} n_2,\text{eHe} M_{12,\text{eHe}} v_{12,\text{eHe}}} = \frac{N_1,\text{nHe} M_{12,\text{nHe}} R_{12,\text{nHe}}}{N_1,\text{eHe} M_{12,\text{eHe}} R_{12,\text{eHe}}}, \]

where we add the subscripts “nHe” and “eHe” to all the variables for the naked-He and enveloped-He cases, respectively. We can obtain the second equality, considering that both of \( n_2,\text{nHe} \) and \( n_2,\text{eHe} \) are the number density of heavy MS stars, and both of \( v_{12,\text{nHe}} \) and \( v_{12,\text{eHe}} \) are velocity dispersion in open clusters. The number ratio of \( N_1,\text{nHe}/N_1,\text{eHe} \) can be interpreted as the ratio of lifetimes of naked He and enveloped He stars, which should be \( \sim 2 \) in solar metallicity. We set \( M_{1,\text{nHe}}/M_{1,\text{eHe}} \sim 0.7 \), supposing that naked He stars have \( \sim 20 \text{M}_\odot \), and enveloped He stars and heavy MS stars have \( \sim 50 \text{M}_\odot \). Although \( R_{12,\text{nHe}} \) and \( R_{12,\text{eHe}} \) are the sum of the radii of two colliding stars, one of two stars has a much larger radius than the other for both of the naked-He and enveloped-He cases. Thus, \( R_{12,\text{nHe}} \) and \( R_{12,\text{eHe}} \) are radii of heavy MS stars and enveloped He stars, respectively, and their ratio \( (R_{12,\text{nHe}}/R_{12,\text{eHe}}) \) should be \( \sim 0.01 \). Then, we obtain the collision-rate ratio such that

\[ \Gamma_{\text{nHe}}/\Gamma_{\text{eHe}} \sim 10^{-2} \left( \frac{N_1,\text{nHe}/N_1,\text{eHe}}{2} \right) \left( \frac{M_{12,\text{nHe}}/M_{12,\text{eHe}}}{0.7} \right) \left( \frac{R_{12,\text{nHe}}/R_{12,\text{eHe}}}{0.01} \right). \]

We therefore estimate that one of \( \sim 100 \) PI-gap BHs is formed through collisions between heavy MS stars and naked He stars. This estimate is consistent with the argument of Di Carlo et al. (2019b) that all the PI-gap BHs in their simulations are formed through collisions between heavy MS and enveloped He stars. In their simulations, only \( \lesssim 20 \) PI-gap BHs are formed in solar metallicity environment.

The solid red curve in Fig. 1 of Di Carlo et al. (2019b), in which the stellar mass drops just before collision, might indicate a collision between heavy MS and naked He stars. This is because the He star largely loses its envelope just before the collision. However, it might be regarded as the enveloped-He case. In the SSE code (Hurley et al. 2000), enveloped-He stars are assumed to have radii of \( \sim 10^3 R_\odot \), even if they lost most of their envelopes. If it is the naked-He case, we can estimate the fraction of BH via naked-He star to that via enveloped-He star, which corresponds to \( \Gamma_{\text{nHe}}/\Gamma_{\text{eHe}} \) from the result of Di Carlo et al. (2019b). In Di Carlo et al. (2019b), 1 of 6 PI-gap BHs involving BH-BH mergers was possibly a naked-He star. This suggests that \( \Gamma_{\text{nHe}}/\Gamma_{\text{eHe}} = 1/6 \sim 0.2 \). Thus, we might underestimate \( \Gamma_{\text{nHe}}/\Gamma_{\text{eHe}} \) by more than 10 times for uncertain reasons, but we conservatively adopt \( \Gamma_{\text{nHe}}/\Gamma_{\text{eHe}} \sim 10^{-2} \).
Finally, we can calculate the formation rate of LB-1-like progenitors from equation (1) as

\[ \dot{N}_{\text{LB-1},p} \sim 3 \times 10^{-8} \left( \frac{\rho_{\text{oc}}}{10^4 M_{\odot} \text{pc}^{-3}} \right) \text{[yr}^{-1}] \].

Here, we leave the factor of \( \rho_{\text{oc}} \), because the typical initial density of open clusters is still uncertain and may be higher than \( 10^4 M_{\odot} \text{pc}^{-3} \) (Portegies Zwart et al. 2010; Fujii & Portegies Zwart 2016).

3 Tidal circularization

In previous section, we estimate the formation rate of LB-1-like progenitors. The LB-1-like progenitors have high eccentricities due to the collisions. They should be circularized, since the eccentricity of the LB-1 system is \( \sim 0.03 \). A circularization mechanism is necessary to explain the nearly zero eccentricity of the LB-1 system. Here, we evaluate the tidal circularization timescale after the collision.

In the case of binary evolution, the most powerful circularization process is tidal interaction. The efficiency of the tidal interaction depends on the type of the stellar envelope. If the envelope is convective, the tidal interaction is the equilibrium tide (Zahn 1989). On the other hand, if the envelope is radiative, the tidal interaction is the dynamical tide (Zahn 1975). In order to determine the type of the tidal effect, we consider the type of the envelopes of the collision products. A collision product has a central He core made from a naked He star with \( 20 M_{\odot} \), and an H envelope made from a heavy MS star with \( 50 M_{\odot} \). Such a star has a convective envelope only when its radius is \( \gtrsim 10^7 R_\odot \), much larger than the semi-major axis of the LB-1 system. Thus, only the dynamical tide with radiative damping can circularize LB-1-like progenitors.

We use the circularization timescale of the dynamical tide with radiative damping derived by Zahn (1977), which is

\[ \tau_{\text{cir,dyn}} = \frac{2}{21} \left( \frac{G M_{\text{coll}}}{R_{\text{coll}}^3} \right)^{\frac{2}{3}} \left( \frac{M_{\text{coll}}}{M_B} \right)^{\frac{1}{2}} \left( 1 + \frac{M_B}{M_{\text{coll}}} \right)^{-\frac{1}{2}} E_2^{-1} \left( \frac{R_{\text{coll}}}{a} \right)^{-\frac{11}{2}}, \]

where \( M_{\text{coll}} \) and \( R_{\text{coll}} \) are the mass and radius of the collision product, respectively, \( a \) is the binary separation, and \( E_2 \) is the second order tidal coefficient. Zahn (1975) fitted \( E_2 \) as

\[ E_2 = 1.592 \times 10^{-9} M_{\text{coll}}^{2.84}. \]

We give \( M_{\text{coll}} = 70 M_\odot \), \( M_B = 8 M_\odot \), and \( a = 1 \text{ au} \), which are the binary parameter of the LB-1 system, and calculate the above equation as

\[ \tau_{\text{cir,dyn}} \sim 5 \times 10^4 \left( \frac{R_{\text{coll}}}{100 R_\odot} \right)^{-9} \text{ yr}. \]

Since the lifetimes of the collision products are similar to that of the naked He stars, \( \sim 0.2 \text{ Myr} \), the binaries should be soon circularized if the collision products have radii of \( \gtrsim 100 R_\odot \). Note that the circularization timescale is \( \sim 10^3 \text{ yr} \) at \( R_{\text{coll}} \sim 200 R_\odot \) due to the sharp dependence on the radii of the collision products.

Although we do not know the initial radii of the collision products, they should be larger than the radii of the colliding MS stars, i.e. \( \gtrsim 100 R_\odot \). The collision products expand on Kelvin-Helmholtz timescale:

\[ t_{\text{KH}} \lesssim 2 \times 10^5 \left( \frac{M_{\text{coll}}}{70 M_\odot} \right)^2 \left( \frac{R_{\text{coll}}}{10 R_\odot} \right)^{-1} \left( \frac{L_{\text{coll}}}{10^3 L_\odot} \right)^{-1} \text{[yr]}. \]

Since the lifetime of the collision product is \( \sim 0.2 \text{ Myr} \), the collision product should expand to \( \gtrsim 100 R_\odot \).

When the radius of the collision products exceed \( \sim 200 R_\odot \) (or \( \sim 1 \text{ au} \)), the binaries start Roche-lobe overflow. Since the mass ratios of the collision products to the B-type stars are about 10, the separations of the binaries become small so quickly that the Roche-lobe overflow becomes unstable. Such binaries should undergo common envelope evolution. The common envelope evolution blows the envelopes of the collision products, and the collision products collapse to BHs as massive as the pre-existing naked He stars, not PI-gap BHs. Thus, if the collision products expand to \( \gtrsim 200 R_\odot \), the LB-1-like progenitors cannot become LB-1-like systems. Since \( t_{\text{KH}} \sim 2 \times 10^4 \text{ yr} \) at \( R_{\text{coll}} \sim 100 R_\odot \), and the lifetime of the collision products are 0.2 Myr, the probability that the collision products collapse to PI-gap BHs at \( R_{\text{coll}} \sim 100-200 R_\odot \) is estimated to be 10 %. Note that the collapse time of the collision products is at random during their lifetimes, since their He cores are originally naked He stars, and are wandering a long time before their collisions.

Combining this with the results of the previous section, we finally obtain the number of LB-1-like systems in the MW galaxy as
The lifetime of LB-1-like systems is the lifetime of B-type stars, $T_B$. After B-type stars end their evolution, LB-1-like systems cannot be observed. We consider a LB-1-like progenitor consisting of a collision product and O-type star with $\sim 25 M_\odot$, not a B-type star. When the radius of the collision product exceeds $\sim 200 R_\odot$, stable Roche-lobe overflow (not common envelope evolution) starts, since the collision product has a radiative envelope, and the mass ratio of the collision product to the O-type star is less than three. Then, the binary always survive and is circularized, although only 10% of a binary survives for the case of a B-type companion star. If the Roche-lobe overflow does not reduce a significant mass fraction of the collision product, the collision product collapses to a PI-gap BH. Then, a LB-1-like system appears, although the system has an O-type star. Since the O-type star has a lifetime of $\sim 7$ Myr, we can estimate the number of such LB-1-like systems in the MW galaxy as

$$N_{\text{LB1}} \sim 0.2 (\rho_{\text{oc}}/10^4 M_\odot \text{pc}^{-3}) (T_B/7\text{Myr}) \left[ M_B \gtrsim 25 M_\odot \right],$$

where $T_B$ and $M_B$ are the lifetime and mass of an O-type star. Finally, this mechanism is not efficient enough to explain the presence of the LB-1 system, even if we assume companion stars of PI-gap BHs to be O-type stars.

### 4 Other possible scenarios

#### 4.1 Stellar collisions

We can divide stellar types into three: MS stars, enveloped He stars, and naked He stars. Collisions with enveloped He stars do not work. Such stars have radii of $\gtrsim 10^3 R_\odot$, more than 1 au. The collision products swallow companion stars when the binary separations are $\sim 1$ au. We consider collisions between two MS stars, and between two naked He stars. Their total masses should exceed $70 M_\odot$. Then, they cannot avoid PPISNe/PISNe. Thus, such collisions do not work for the formation of the LB-1 system. Finally, collisions between MS and naked He stars have a event rate not enough to explain the formation of the LB-1 system described in the previous sections. In summary, any types of stellar collisions cannot explain the presence of the LB-1 system.

#### 4.2 Capture scenarios

As seen in section 2, many PI-gap BHs are formed in open clusters. In this section, we consider whether they can capture B-type stars, and whether they can form LB-1-like systems.

##### 4.2.1 Open clusters

We first estimate the number of binaries with PI-gap BHs and B-type stars, $N_b$. It is expressed as

$$N_b = \Gamma_{\text{cap}} T_B,$$

where $\Gamma_{\text{cap}}$ is a rate at which PI-gap BHs capture B-type stars. We calculate $\Gamma_{\text{cap}}$, supposing this capture mechanism is encounters between PI-gap BHs and binaries with B-type stars. We calculate this rate, using equations (4) and (6). In this case, $N_1$ is the number of PI-gap BHs, which can be given by

$$N_1 \sim \dot{N}_{\text{PIgap}} T_B \sim 80 \left( \frac{\rho_{\text{oc}}}{10^4 M_\odot \text{pc}^{-3}} \right) \left( \frac{T_B}{40 \text{Myr}} \right),$$

where we adopt the value in equation (3) for $\dot{N}_{\text{PIgap}}$, and the lifetime of $8 M_\odot$ stars for $T_B$. For $n_2$, we choose the number density of MS stars with more than $8 M_\odot$. Then, $n_2$ can be calculated as

$$n_2 = \eta_b \rho_{\text{oc}} \sim 7 \times 10^{-55} \left( \frac{\eta_b}{0.02 M_\odot} \right) \left( \frac{\rho_{\text{oc,late}}}{10^3 M_\odot \text{pc}^{-3}} \right) \left[ \text{cm}^3 \right],$$

where $\rho_{\text{oc,late}}$ is mass density of open clusters after PI-gap BHs are formed. Since open clusters have lost large amounts of mass by that time, $\rho_{\text{oc,late}}$ should be much less than $\rho_{\text{oc}}$. The sweeping volume $V_{12}$ should be

$$V_{12} \sim 1 \times 10^{37} \left( \frac{M_{12}}{100 M_\odot} \right) \left( \frac{R_{12}}{1 \text{au}} \right) \left( \frac{v_{12}}{1 \text{kms}^{-1}} \right)^{-1} \left[ \text{cm}^3 \text{s}^{-1} \right],$$

where we adopt PI-gap BH mass for $M_{12}$, semi-major axes of the LB-1 system for $R_{12}$, and velocity dispersion in open clusters for $v_{12}$. Finally, we get $N_0$ as...
\[N_b \sim 0.7 \left( \frac{\rho_{\text{pc}}}{10^4 M_\odot \text{pc}^{-3}} \right) [M_B \gtrsim 8 M_\odot]. \] (20)

These binaries are eccentric LB-1-like systems due to the binary-single encounters, and however they cannot be circularized after their formation as follows. The B-type stars are MS stars, and have radiative envelopes. Since their radii are \( \gtrsim 10 R_\odot \), the circularization timescale is \( \tau_{\text{cir}} \sim 5 \times 10^3 \) yr according to equation (12). This is much larger than the lifetimes of the B-type stars. Thus, their eccentricities keep constant from their formation time to their ending time.

We estimate the probability that these binaries have nearly zero eccentricities, say \( \lesssim 0.05 \). We assume that binary-single encounters leave binaries with eccentricities in the thermal distribution (Heggie 1975). The probability of these binaries with eccentricities of \( \lesssim 0.05 \) is \( \sim 10^{-3} \). Thus, this mechanism does not work for the formation of the LB-1 system.

The above number of eccentric LB-1-like systems put strong constraints on any other capture scenarios in open clusters. This is because the above scenario has the highest event rate among the capture scenarios in open clusters. For example, let’s consider collision of a PI-gap BH with a MS star whose companion star is a B-type star. We assume that a binary consisting of the collision product and B-type star receives tidal friction through unknown processes much more efficiently than we consider in section 3, and that a LB-1-like system is formed. However, the collision rate is \( \sim 10 \) times less than the capture rate of B-type stars by PI-gap BHs discussed above, since the radius of a MS star is \( \sim 10 R_\odot \) less than the semi-major axis of the LB-1 system \( (\sim 1 \) au) by \( \sim 10 \). Thus, before the discovery of LB-1-like systems formed through this mechanism, we should discover eccentric LB-1-like systems formed through capture of B-type stars by PI-gap BHs. Although radial velocity observations can discover circular binaries more easily than eccentric binaries, the detection efficiency for circular binaries is more than for eccentric binaries only by \( 10 \% \) (Shen & Turner 2008). In summary, any capture scenarios do not work for the formation of the LB-1 system.

4.2.2 Globular clusters

Many PI-gap BHs should be formed in globular clusters. We consider whether they can form LB-1-like systems. Since globular clusters are old in the MW galaxy (\( \gtrsim 10 \) Gyr), their turnoff masses should be \( \sim 0.8 M_\odot \). Thus, even if turnoff stars merge, and form blue stragglers, their masses should be \( \sim 1.6 M_\odot \). They are not B-type stars. In summary, PI-gap BHs in globular clusters cannot capture B-type stars, since there is no B-type star in globular clusters. Thus, LB-1-like systems cannot be formed in globular clusters.

4.2.3 Interstellar space

Pop. II/III stars form a large number of merging BH-BHs with the total masses of \( \sim 70 M_\odot \), and form PI-gap BHs (e.g. Kinugawa et al. 2014;Belczynski et al. 2016a). Thus, many PI-gap BHs should be wandering in the MW galaxy. We assess whether they can capture B-type stars in the MW galaxy. We suppose this mechanism is binary-single encounters as the same in section 4.2.1.

The number of such binaries can be written in the same way as equations (16). However, we should calculate \( \Gamma_{\text{cap}} \) in a different way. We adopt the number of Pop. III PI-gap BHs for \( N_1 \), and estimate it from Kinugawa et al. (2014) as

\[ N_1 \sim 10^5. \] (21)

We calculate \( n_2 \) as the number density of B-type stars in the MW galaxy in the following:

\[ n_2 = \frac{\eta_B \dot{M}_{\text{now}} T_{\text{lb}}}{4/3 \pi R_{\text{now}}^3} \sim 10^{-62} \left( \frac{\eta_B}{0.01 M_\odot^{-1}} \right) \left( \frac{\dot{M}_{\text{now}}}{2 M_\odot \text{yr}^{-1}} \right) \left( \frac{T_{\text{lb}}}{40 \text{Myr}} \right) \left( \frac{R_{\text{now}}}{10 \text{kpc}} \right)^{-3} \text{[cm}^{-3}] \] (22)

where \( R_{\text{now}} \) is the size of the MW galaxy. Although B-type stars are formed in the MW disk, Pop. III PI-gap BHs should be wandering in the MW halo. Thus, we assume B-type stars spread in the MW halo. The sweeping volume is given by

\[ V_{12} \sim 6 \times 10^{34} \left( \frac{M_{12}}{100 M_\odot} \right) \left( \frac{R_{12}}{1 \text{au}} \right) \left( \frac{v}{200 \text{km} \text{s}^{-1}} \right)^{-1} \text{[cm}^3 \text{s}^{-1}], \] (23)

where we adopt the MW circular velocity for \( v_{12} \). Putting together the above equations, we obtain the capture rate as

\[ N_{\text{bin}} \sim 7 \times 10^{-8} [M_B \gtrsim 8 M_\odot]. \] (24)

If we also take into account Pop. II PI-gap BHs, the number should be increased slightly.

Any other capture scenarios in interstellar space do not work. The above event rate is the highest among any capture scenarios in interstellar space, similarly to the discussion in section 4.2.1.
4.3 Hierarchical triple system
We explore the possibility that LB-1-like systems are formed from hierarchical triple systems. We consider a hierarchical triple system which has an inner binary consisting of heavy MS stars, and a B-type star as the third star. Since the inner binary has to leave a PI-gap BH through merger/collision, we can assume their total mass to be $\sim 100M_\odot$ and the third star to be $\sim 10M_\odot$. We can also assume that the outer binary has semi-major axis of $a_{\text{out}} \sim 1$ au, while the inner binary has semi-major axis of $a_{\text{in}} \sim 10 - 100R_\odot$. If $a_{\text{in}} < 10R_\odot$, the inner binary merges when they are MS stars. If $a_{\text{out}} > 100R_\odot$, the hierarchical triple system is unstable (Harrington 1972; Mardling & Aarseth 1999).

The inner binary cannot leave a PI-gap BH through pure binary evolution for the following reason. In order to produce a PI-gap BH, they have to merge when the primary star is an enveloped He star, and the secondary star is a MS star. This merger should be driven by common envelope evolution. We assess whether the inner binary satisfies conditions of the onset criteria of common envelope evolution. Since $a_{\text{in}} \lesssim 100R_\odot$, the primary star has a radiative envelope when it begins interacting with the secondary star. Therefore, the mass ratio of the primary star to the secondary star should be large (more than three). In order to produce a LB-1-like system, on the other hand, the secondary star should have $\gtrsim 50M_\odot$, since the common envelope evolution blows away the primary envelopes and leaves the He core of the primary star with a mass of $\sim 20M_\odot$. Thus, the primary star initially should have $\gtrsim 150M_\odot$ because in the case of solar metallicity, stellar wind halves the initial mass by the end of the MS phase. However, if the primary star has $> 150M_\odot$, its radius must exceed $100R_\odot$ before the end of the MS phase, and it merges with the secondary star. Since both of the primary and secondary stars are MS stars, their merger remnant is also a MS star. It makes a large He core, and cannot leave a PI-gap BH due to PPISN/PISN.

The inner MS-MS binary may collide through secular interaction between the outer binary before either of them evolves to an enveloped He star. Here, we take into account Kozai-Lidov (KL) mechanism as secular interaction (Kozai 1962). The KL timescale can be expressed as

$$T_{\text{KL}} = \frac{2\pi}{Gm_1} \left( \frac{a_{\text{in}}}{M_3} \right)^{1/2} \left( \frac{a_{\text{in}}}{a_{\text{out}}} \right)^{3/2} (1 - e^2_{\text{out}}),$$

where $m_1$ and $M_3$ are the masses of the inner binary and third star, and $e_{\text{out}}$ is the eccentricity of the outer binary. This can be calculated as

$$T_{\text{KL}} \lesssim 100 \left( \frac{m_1}{100M_\odot} \right)^{1/2} \left( \frac{M_3}{10M_\odot} \right)^{-1} \left( \frac{a_{\text{in}}}{10R_\odot} \right)^{-3/2} \left( \frac{a_{\text{out}}}{1\text{au}} \right)^{3} \text{[yr]},$$

where the equal sign of the above equation is held for $e_{\text{out}} = 0$. Therefore, if KL mechanism works, the inner binary merges before the primary star evolves to an enveloped He star. From the above discussion, we conclude that hierarchical triple systems cannot form LB-1-like binaries.

5 Summary
We assess various mechanisms forming LB-1-like systems through dynamical interactions, not assuming the reduction of stellar wind mass loss. The most efficient mechanism is collision of naked He stars with heavy MS stars which have B-type companion stars in open clusters. The number of LB-1-like systems formed through this mechanism is estimated to be $\sim 0.1(\rho_{oc}/10^4M_\odot\text{pc}^{-3})$ in the MW galaxy. If we take into account LB-1-like systems with O-type stars as companion stars, the number increases to $\sim 0.3(\rho_{oc}/10^4M_\odot\text{pc}^{-3})$.

This mechanism can form LB-1-like systems at least 100 times more efficiently than any other mechanisms: capture of B-type stars by PI-gap BHs, stellar collisions between other type stars, and stellar mergers in hierarchical triple systems. Especially, capture scenarios result in too many eccentric binaries. If one of the capture scenarios formed the LB-1 system, we would have detected eccentric LB-1-like systems earlier than the LB-1 system.

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References
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016a, Physical Review Letters, 116, 241103
Abdul-Masih, M., Banyard, G., Bodensteiner, J., et al. 2019, No signature of the orbital motion of a putative 70 solar mass black hole in LB-1, arXiv:1912.04092
Banerjee, S., Kroupa, P., & Oh, S. 2012, ApJ, 746, 15
Belczynski, K., Bulik, T., Fryer, C. L., et al. 2010, ApJ, 714, 1217
Belczynski, K., Holz, D. E., Bulik, T., & O’Shaughnessy, R. 2016a, Nature, 534, 512
Belczynski, K., Heger, A., Gladysz, W., et al. 2016b, A&A, 594, A97
Belczynski, K., Hirschi, R., Kaiser, E. A., et al. 2019, arXiv e-prints, arXiv:1911.12357
Berti, E., Cardoso, V., Gonzalez, J. A., et al. 2007, Phys. Rev. D, 76, 064034
Bland-Hawthorn, J., & Gerhard, O. 2016, ARA&A, 54, 529
Bond, J. R., Arnett, W. D., & Carr, B. J. 1984, ApJ, 280, 825
Campanelli, M., Lousto, C. O., Zlochower, Y., & Merritt, D. 2007, Phys. Rev. Lett., 98, 231102
Chatzopoulos, E., & Wheeler, J. C. 2012, ApJ, 748, 42
Di Carlo, U. N., Giacobbo, N., Mapelli, M., et al. 2019a, MNRAS, 487, 2947
Di Carlo, U. N., Mapelli, M., Bouffanais, Y., et al. 2019b, arXiv e-prints, arXiv:1911.01434
Dong, S., Katz, B., Kushnir, D., & Prieto, J. L. 2015, MNRAS, 454, L61
El-Badry, K., & Quataert, E. 2019, Not so fast: LB-1 is unlikely to contain a 70 $M_\odot$ black hole, arXiv:1912.04185
Eldridge, J. J., Stanway, E. R., Breivik, K., et al. 2019, Weighing in on black hole binaries with BPASS: LB-1 does not contain a 70$M_\odot$ black hole, arXiv:1912.03599
Fryer, C. L., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 372
Fujii, M. S., & Portegies Zwart, S. 2011, Science, 334, 1380
Gaburov, E., Lombardi, James C., J., & Portegies Zwart, S. 2010, MNRAS, 402, 105
Giesers, B., Dreizler, S., Husser, T.-O., et al. 2018, MNRAS, 475, L15
Groh, J. H., Farrell, E., Meynet, G., et al. 2019, arXiv e-prints, arXiv:1912.00994
Harrington, R. S. 1972, Celestial Mechanics, 6, 322
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
Heggie, D. C. 1975, MNRAS, 173, 729
Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, MNRAS, 315, 543
Kinugawa, T., Inayoshi, K., Hotokezaka, K., Nakauchi, D., & Nakamura, T. 2014, MNRAS, 442, 2963
Kozai, Y. 1962, AJ, 67, 591
Kroupa, P. 2001, MNRAS, 322, 231
Kumamoto, J., Fujii, M. S., & Tanikawa, A. 2019, MNRAS, 486, 3942
Leung, S.-C., Nomoto, K., & Blinnikov, S. 2019, arXiv e-prints, arXiv:1901.11136
Lorén-Aguilar, P., Isen, J., & García-Berro, E. 2010, MNRAS, 406, 2749
Lousto, C. O., Campanelli, M., Zlochower, Y., & Nakano, H. 2010, Classical and Quantum Gravity, 27, 114006
Mardling, R., & Aarseth, S. S., 1999, in NATO Advanced Science Institutes (ASI) Series C, Vol. 522, NATO Advanced Science Institutes (ASI) Series C, ed. B. A. Steves & A. E. Roy, 385
Misiriotis, A., Kilouris, E. M., Papamastorakis, J., Boumis, P., & Goudis, C. D. 2006, A&A, 459, 113
Piskunov, A. E., Schilbach, E., Kharchenko, N. V., Röser, S., & Scholz, R. D. 2007, A&A, 468, 151
Portegies Zwart, S. F., McMillan, S. L. W., & Gieles, M. 2010, ARA&A, 48, 431
Raskin, C., Timmes, F. X., Scannapieco, E., Diehl, S., & Fryer, C. 2009, MNRAS, 399, L156
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Rodríguez, C. L., Zevin, M., Amaro-Seoane, P., et al. 2019, Phys. Rev. D, 100, 043027
Rosswog, S., Kasen, D., Guillochon, J., & Ramirez-Ruiz, E. 2009, ApJL, 705, L128
Sana, H., de Mink, S. E., de Koter, A., et al. 2012, Science, 337, 444
Shen, R. F., Matzner, C. D., Howard, A. W., & Zhang, W. 2019, arXiv e-prints, arXiv:1911.12581
Shen, Y., & Turner, E. L. 2008, ApJ, 685, 553
Spera, M., Mapelli, M., Giacobbo, N., et al. 2019, MNRAS, 485, 889
Thompson, T. A., Kochanek, C. S., Stanek, K. Z., et al. 2019, Science, 366, 637
Venumadhav, T., Zackay, B., Roulet, J., Dai, L., & Zaldarriaga, M. 2019, arXiv e-prints, arXiv:1904.07214
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2001, A&A, 369, 574
Woosley, S. E., Blinnikov, S., & Heger, A. 2007, Nature, 450, 390
Zackay, B., Dai, L., Venumadhav, T., Roulet, J., & Zaldarriaga, M. 2019, arXiv e-prints, arXiv:1910.09528
Zahn, J. P. 1975, A&A, 41, 329
—. 1977, A&A, 500, 121
—. 1989, A&A, 220, 112