Gaia’s Detectability of Black Hole-Main Sequence Star Binaries Formed in Open Clusters

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1 Introduction

Stellar mass black holes (BHs) are the remnants of massive stars. They have been detected as X-ray binaries in the Milky Way (MW), which have very short period such as several hours. The number of discovered BHs in this way is less than 100 (Corral-Santana et al. 2016), while theoretical studies have estimated the total number of stellar mass BHs in the MW to be $10^8 - 10^9$ (Shapiro & Teukolsky 1983; van den Heuvel 1992; Brown & Bethe 1994; Samland 1998; Agol et al. 2002).

On the other hand, those in extragalactic distances have been detected by gravitational wave observations (Abbott et al. 2019). These binary BHs also have very short periods and therefore merge by emitting gravitational waves. Thus, observed BHs are so far biased to those with short periods.

There are the other two ways to find binaries including BHs (hereafter, BH binaries) especially with longer orbital periods.
One is radial velocity observations. There are already a few detection reports of long orbital period BH binaries with this method (Giesers et al. 2018; Thompson et al. 2019; Liu et al. 2019). In particular, Liu et al. (2019) have reported a 70\(M_\odot\)-BH in a binary system (but see Eldridge et al. 2019; Tanikawa et al. 2019; Safarzadeh et al. 2019; El-Badry & Quataert 2020; Irrgang et al. 2020). The other is astrometric observations. Gaia mission (Gaia Collaboration et al. 2016) started in 2013 and is providing parallaxes and proper motions of 100 million stars with high spatial resolution, \(\sim\) \(\mu\)as. Until now, Gaia Data Release 2 (DR2) has been released, and the next data release (DR3), which provides information of binaries, is planned in 2021\(^1\). It may include BH binaries with long periods, i.e., days to years. Andrews et al. (2019) investigated the precision of Gaia’s observations by using mock data of Gaia. They theoretically estimated BH binaries with periods of \(10^{-3}\) days will be detected within \(\sim\) 1 kpc with a good precision.

Some previous researches have estimated the number of black hole-main sequence star binaries (hereafter, BH-MS binaries) detectable with Gaia (Mashian & Loeb 2017; Breivik et al. 2017; Yamaguchi et al. 2018; Yalinewich et al. 2018; Kinugawa & Yamaguchi 2018; Shao & Li 2019). All of them were considered to be isolated binaries, which were formed as tight binaries and did not experience any dynamical interactions with other stars in the MW disk. Mashian & Loeb (2017) estimated \(2 \times 10^5\) binaries can be detected in 5\(\sigma\) sensitivity. Breivik et al. (2017) added the effect of BH natal kick on the number of detectable BH-MS binaries. They found that the number of detectable BH-MS binaries do not strongly depend on models of BH natal kick, and the detection with Gaia was estimated to be 3,800–12,000, which is one order of magnitude smaller than Mashian & Loeb (2017). Yamaguchi et al. (2018) demonstrated various kinds of BH mass distributions and also considered interstellar extinction, which has not been included in the previous work. They showed that 200–1,000 BH-MS binaries can be detected, and that the value varies with the distribution models. Breivik et al. (2019) also showed that the observation of such compact objects-giant star binaries will be a good test for wind accretion models.

These previous studies have considered only isolated binaries in the MW disk (field). However, BH-MS binaries are also formed in stellar clusters through dynamical interactions. The aim of this paper is estimating the number of BH-MS binaries formed in open clusters detectable with Gaia. We also show the distribution of binary parameters such as BH and MS masses, orbital period, and eccentricity and the difference from those of isolated binaries.

This paper consists of the following three parts. In section 2, we introduce our method to obtain observable BH-MS binaries formed in open clusters. In section 3, we show the results of \(N\)-body simulation. Finally, we indicate the features of the binaries which may reflect the difference in the formation processes in section 4.

## 2 Method

We use the BH-MS binary distribution obtained from \(N\)-body simulations of open clusters performed in Kumamoto et al. (2020). In this section, we first describe the \(N\)-body simulation methods used in Kumamoto et al. (2020) (section 2.1) and the initial condition of the open cluster models (section 2.2). Finally, we outline how we estimate the number of observable BH-MS binaries by using the \(N\)-body simulation results in section 2.3.

### 2.1 \(N\)-body Simulation

We use NBODY6++GPU (Wang et al. 2015) for the \(N\)-body simulations. NBODY6++GPU is a direct \(N\)-body simulation code based on NBODY6 and NBODY6-GPU (Aarseth 2003; Nitadori & Aarseth 2012, respectively). It employs a fourth-order Hermite integration method (Makino & Aarseth 1992) with KS regularization scheme (Kustaanheimo & Stiefel 1965; Mikkola & Aarseth 1993). Single and binary stellar evolution models are also included (Hurley et al. 2000; Hurley et al. 2002, respectively). We adopt stellar wind mass loss model of Belczynski et al. (2010) and supernova model of Belczynski et al. (2002). We switch off BH natal kicks caused by asymmetric supernova explosion for simplicity.

### 2.2 Initial Condition of Open Clusters

We adopt an initial mass of our open cluster model \(\langle M_{\text{ini}} \rangle\) as \(2.5 \times 10^3 M_\odot\) and the Plummer profile (Plummer 1911) for the phase space distribution. We set the initial half-mass density \(\rho_{\text{hm}} \equiv 3 M_{\text{ini}}/8 \pi r_{\text{hm}}^3\), where \(r_{\text{hm}}\) is the half-mass radius, to be \(10^4 M_\odot\text{pc}^{-3}\). The mass of each particle is randomly assigned following Kroupa initial mass function (Kroupa 2001). We set the minimum and maximum masses as 0.08\(M_\odot\) and 150\(M_\odot\), respectively. Therefore, the average stellar mass \(\langle m \rangle\) is 0.586\(M_\odot\), and the initial number of particles \(\langle N_{\text{ini}} \rangle\) is \(M_{\text{ini}}/\langle m \rangle = 4266\). For the metallicity \(Z\), we adopt solar metallicity, \(Z = 0.02\). We do not include primordial binaries and an external tidal field. We perform 1000 runs with different realizations.

One might think that our cluster model has a mass density much higher than those of currently observed open clusters (Portegies Zwart et al. 2010). However, we note that the ages of observed open clusters are more than a few Myrs. Even if they initially had a mass density of \(\sim 10^4 M_\odot\text{pc}^{-3}\), their density should have decreased due to gas expulsions, supernovae and dynamical evolution (Fujii & Portegies Zwart 2016) (see

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\(^1\) https://www.cosmos.esa.int/web/gaia/release
Kumamoto et al. 2020, for more details).

2.3 Number Estimation

In this subsection, we summarize how we estimate the number of BH-MS binaries observable with Gaia by using the results of our $N$-body simulations. We follow Yamaguchi et al. (2018).

2.3.1 Distribution in the MW

We distribute BH-MS binaries escaping from open clusters in the MW. The number distribution of binaries at a position ($x$) is written as a function of BH mass ($m_{BH}$), MS mass ($m_{MS}$), and orbital period ($P$):

$$n(m_{BH},m_{MS},P,x) = \tilde{N}(m_{BH},m_{MS},P) \times t_{MS} \times \rho(x),$$

where $\tilde{N}(m_{BH},m_{MS},P)$ is defined as

$$\tilde{N}(m_{BH},m_{MS},P) = N(m_{BH},m_{MS},P)/1000M_{\odot} \text{yr}^{-1}kpc^{-2}.$$

We assume that local star-formation rate density is proportional to the local stellar density, and star formation rate ($R_{\text{SF}}$) is the same everywhere in the MW disk. Then, $\rho(x)$ is given by

$$\rho(x) = f_{cl} \times R_{\text{SF}} \times n_{\text{MW}}(x),$$

where $f_{cl}$ is the fraction of stars formed in open clusters and $n_{\text{MW}}(x)$ is the stellar number density distribution at a position ($x$) in the MW.

We consider only the MW disk because the MW bulge cannot be observed due to interstellar extinction. In the MW disk, stars exponentially distribute from the center of the galaxy (de Vaucouleurs 1959; Kormendy 1977) and perpendicular to the galaxy plane (Bahcall & Soneira 1980). The stellar number density distribution $n_{\text{MW}}(x)$ is expressed as

$$n_{\text{MW}}(x) = n_0 \exp \left( -\frac{r-r_0}{r_h} - \frac{z}{h_z} \right).$$

We choose the normalization factor ($n_0$) to satisfy the following equation,

$$4\pi \int_0^{r_{\text{max}}} r dr \int_0^{z_{\text{max}}} dz n_{\text{MW}}(x) = 1,$$

where $r_0$ is a distance from the center of the galaxy to the sun (8.5 kpc), and $r_h$ and $h_z$ are scale heights to the $r$- and $z$-directions (3.5 kpc and 250 pc), respectively. We set $r_{\text{max}} = 30$ kpc and $z_{\text{max}} = 1$ kpc (see a review for Bland-Hawthorn & Gerhard 2016).

For $R_{\text{SF}}$, we adopt a total star formation rate in the entire MW disk ($3.5M_{\odot}$ yr$^{-1}$) (O’Shaughnessy et al. 2008). We assume that clusters have the same total mass and density (single population) and that all clusters form binaries following the same binary distributions. We also assume that a certain fraction ($f_{cl}$) of stars are formed in open clusters and that $f_{cl}$ is a constant. We estimate $f_{cl}$ based on star formation rate surface density in the MW and that in open clusters. According to an observational relationship between the molecular surface density and star formation rate surface density (Bigiel et al. 2008), star formation rate surface density is estimated as $1.5 - 5.1 \times 10^{-3}M_{\odot}$ yr$^{-1}$ kpc$^{-2}$ given the molecular surface density is $3.1M_{\odot}$ yr$^{-1}$ (Guesten & Mezger 1982). The value is $7 - 8$ kpc from the galactic center, that is, 1 kpc from the Sun. We also estimate the star formation rate for stars in open clusters by calculating the total stellar mass of open clusters younger than 100 Myr within 1 kpc from the Sun. By using a catalog of open clusters (Piskunov et al. 2007), we find that $6.6 \times 10^{-4}M_{\odot}$ yr$^{-1}$ forms in open clusters within 1 kpc from the Sun. Therefore, we estimate $f_{cl} \sim 0.1$.

The total number of BH-MS binaries detectable with Gaia ($N_{\text{det}}$) is obtained as

$$N_{\text{det}} = \int dm_{BH} \int dm_{MS} \int dP \int_{|x-x_0|<D_{\text{max}}} d^3x n(m_{BH},m_{MS},P,x),$$

where $x_0$ is the position of the Sun and $D_{\text{max}}$ is the maximum distance dependent on the parameters of the binaries. From the next section, we evaluate $D_{\text{max}}$ by considering some conditions: interstellar extinction and observational constraints.

2.3.2 Interstellar Extinction

We calculate the maximum distance at which the MS of a binary is luminous enough to be observed with Gaia. Here, we call it $D_{\text{MS}}$. Considering interstellar extinction, $D_{\text{MS}}$ depends on MS mass ($m_{MS}$), and it satisfies the equation below,

$$m_V(m_{MS},D_{MS}) = m_{V,\text{lim}},$$

where $m_{V,\text{lim}}$ is the maximum apparent magnitude observable with Gaia. We adopt $m_{V,\text{lim}} = 20$ (Gaia Collaboration et al. 2016). Following Yamaguchi et al. (2018), we adopt V band instead of the Gaia band because the color $V - I$ is less than 1 (Jordi et al. 2010). We use the empirical relationship between MS mass ($m_{MS}$) and its absolute magnitude in V band ($M_V$) (Smith 1983) is

$$m_{MS} = \begin{cases} 10^{-0.1(M_V-4.8)} & (M_V < 8.5) \\ 1.9 \times 10^{-0.17(M_V-4.8)} & (M_V > 8.5). \end{cases}$$

The apparent magnitude ($m_V$) is calculated by using

$$M_V = m_V - 5(2 + \log_{10}D_{\text{kpc}}) - A_V(D_{\text{kpc}}),$$

where $D_{\text{kpc}}$ is the distance to the binary in kpc and $A_V$ is interstellar extinction. Since the average extinction in the MW is $\sim 1$ mag per 1 kpc in V band (Spitzer 1978; Shafter 2017), we adopt $A_V \sim D_{\text{kpc}}$. Therefore, we obtain $D_{\text{MS}}$ satisfying the
equation:
\[ M_V + 5(2 + \log_{10} D_{MS}) + D_{MS} = 20, \]  
(10)
where \( D_{MS} \) is in kpc.

### 2.3.3 Observational Constraints on Detection of BHs

We identify a binary with a MS and an unseen object by observing the motion of the MS. In order to determine the unseen object as a BH, the lower mass limit of the unseen object should be heavier than \( 3M_\odot \) (Kalogera & Baym 1996). In other words, the estimated mass of the unseen object should satisfy an equation:
\[ m_{BH} - m_{BH} > 3M_\odot, \]  
(11)
where \( m_{BH} \) is the mass of an unseen object and \( \sigma_{BH} \) is its standard error. We set \( n = 1 \) following Yamaguchi et al. (2018).

The observables of a binary are the MS mass \( (m_{MS}) \), the binary orbital period \( (P) \), the angular semi-major axis \( (a_*) \), and the distance to the binary \( (D) \). Their relationship is expressed as
\[ \frac{(m_{MS} + m_{BH})^2}{m_{BH}} = \frac{G}{4\pi^2} \frac{P^2}{(a_*)D^3}, \]  
(12)
where \( G \) is the gravitational constant. From this equation, we relate the standard error of BH mass \( (\sigma_{BH}) \) to standard errors of other binary parameters. We can derive the relationship of the standard error of each parameter:
\[ \left( \frac{\sigma_{BH}}{m_{BH}} \right)^2 = \left( \frac{3}{2} - \frac{m_{BH}}{m_{BH} + m_{MS}} \right)^{-2} \times \left[ \left( \frac{m_{MS}}{m_{BH} + m_{MS}} \right)^2 \frac{\sigma^2_P}{m_{MS}^2} + \frac{\sigma^2_D}{P^2} + \frac{9}{4} \left( \frac{\sigma^2_a}{a_*^2} + \frac{\sigma^2_D}{D} \right) \right]. \]  
(13)
where \( \sigma_{MS} \) is a standard error of the MS mass, \( \sigma_P \) is that of the binary orbital period, \( \sigma_a \) is that of the angular semi-major axis, and \( \sigma_D \) is that of the distance. Here, we assume that each standard error is sufficiently smaller than each observable, and ignore the correlation among the observables.

If we assume that each error should be smaller than 10% of the value of each variable for detection, that is,
\[ \sigma_{MS}/m_{MS} < 0.1, \quad \sigma_P/P < 0.1, \quad \sigma_a/a_* < 0.1, \quad \text{and} \quad \sigma_D/D < 0.1, \]  
(14)
BHs with masses of \( \gtrsim 3.75M_\odot \) can be detected. There are only few BHs lighter than \( 5M_\odot \) (Özel et al. 2010). Therefore, we consider the constraints shown in equation (14) as stiff enough for detection of all BH-MS binaries.

In particular, the first and second conditions in equation (14) are easily achieved. According to Tetzlaff et al. (2011), a typical standard error of a stellar mass estimated from its spectral and luminosity is smaller than 10%. That of an orbital period can be limited to \( \lesssim 10\% \) if the observed period is shorter than two-thirds of the observational time (ESA 1997). For Gaia, it is 5 years and we adopt 3 years (\( \sim 5 \times 2/3 \)) to the maximum period. We also set the minimum period as 1 day.

For the rest conditions, we can obtain additional constraints on \( D_{max} \). Since a parallax \( p \) is proportional to \( 1/D \), we can derive the following equation:
\[ \frac{\sigma_p}{p} \sim \frac{\sigma_D}{D} < 0.1, \]  
(15)
where \( \sigma_p \) is a standard error of a parallax. Gaia Collaboration et al. (2016) have expressed that in G band \( \sigma_p \) as
\[ \sigma_p = (-1.631 + 680.8z(m_\nu) + 32.73z(m_\nu)^2)^{1/2}[\mu \text{as}], \]  
(16)
where
\[ z(m_\nu) = 10^{0.4(max[12.09, m_\nu] - 15)}. \]  
(17)

Note that we neglect the dependence on the \((V - I)\) color. Substituting equation (16) into equation (15), we obtain the condition of a distance as
\[ (-1.631 + 680.8z(m_\nu) + 32.73z(m_\nu)^2)^{1/2} < 10^2/\mu \text{as} \]  
(18)

We should take care that \( p \sim 10^3/D_{\mu \text{as}} \), when \( p \) is in \( \mu \text{as} \) and \( D_{\mu \text{as}} \) is in kpc. Hereafter, the maximum distance satisfying this equation is called \( D_p \).

Finally, the constraint from a semi-major axis set another constraint on \( D_{max} \). Since the semi-major axis of each binary is close to the orbital radius on celestial sphere, the standard error of semi-major axis \( (\sigma_a) \) is \( \sim \sigma_P \). Therefore, the constraint from the semi-major axis of a binary which can be observed with Gaia is
\[ a > 10\frac{m_{BH} + m_{MS}}{m_{BH}} D_{\sigma_P}, \]  
(19)
and we obtain the maximum distance satisfying the equation above and assign it to \( D_a \).

Therefore, by substituting \( D_{MS}, D_p, \) and \( D_a \) to \( D_{max} \), we can include each constraint. We set the maximum distance considering no effects as 10 kpc.

### 3 Results

#### 3.1 Properties of Escaping BH-MS Binaries

According to the results of \( N \)-body simulations, we investigate the parameters of BH-MS binaries escaping from all the open clusters.

Figure 1 shows MS mass and orbital period distribution of all the BH-MS binaries escaping from open clusters. We obtain 225 binaries and divide them into four groups. Since we assume that Gaia can observe binaries whose orbital periods are \( \sim 1 \) day to 3 years, we separate the binaries mainly based on their orbital period. We call a group of binaries with heavier MS masses \( (m_{MS} \gtrsim 5.6M_\odot) \) and orbital periods shorter than 3 years as Group 1. We categorize binaries with orbital periods shorter than 3 years but with lighter MS masses \( (m_{MS} \sim 1.8 - 5.6M_\odot) \) as Group 2. Most of the other binaries have orbital periods between 3 years and 270 years. We call
Fig. 1. MS mass $m_{\text{MS}}$ and orbital period $P$ distribution of the binaries escaping from all the open clusters.

Fig. 2. The scheme of the formation process of Group 2 binaries.

Table 1. The total number of BH-MS binaries observable with Gaia ($N_{\text{det}}$) for each model. “10 kpc model”: the number of binaries within 10 kpc from the Sun, “Breivik model”: the number with the observational constraint from parallaxes in 3\(\sigma\) confidence level. “Yamaguchi model”: the number with interstellar extinction and the observational constraints from parallaxes and orbital separations.

|                | $N_{\text{det}}$ | Group 1 | Group 2 |
|----------------|------------------|---------|---------|
| 10 kpc model   | $2.0 \times 10^3$| 14      | $2.0 \times 10^3$ |
| Breivik model  | $7.1 \times 10^2$| 14      | $6.9 \times 10^2$  |
| Yamaguchi model| $8.9$            | $5.6 \times 10^{-4}$ | 8.9 |

Fig. 3. Two-dimensional histogram for the numbers of all the escaping binaries from open clusters within 10 kpc from the Sun. The gray scale shows the number of BH-MS binaries supposed to exist within 10 kpc from the Sun.

We find that Group 1 binaries are formed through three-body encounters and binary-single interactions when they were MSs. They experience common envelope phases, and one of the binary MSs evolve to BHs. Until they escape from open clusters, they have not closely interact with any other stars. Thus, Group 1 binaries are a kind of isolated binaries after they were formed.

Most of Group 2 binaries are formed as follows. Single massive stars evolve to BHs and capture MSs to form binaries. They experience common envelope phase, and evolve to BH-compact object such as white dwarf (WD) binaries. Figure 2 is the schematic figure of this formation process. The rest of Group 2 binaries experience common envelope phases, while they are MS-MS binaries and evolve to BH-MS binaries. Finally, all of Group 2 binaries exchange one of their members with MSs and escape from open clusters.

The mass gap between Groups 1 and 2 is a trade-off region. A MS in such mass region is neither heavy enough to form a binary nor light enough to be weighted by the initial mass function (heavier stars are less likely to be formed).

Group 3 binaries are formed by three-body encounters and binary-single encounters including BHs and MSs. The BHs evolve from MSs in single stellar evolution. Group 3 binaries have orbital periods characterized by the escape velocities of open clusters.

Group 4 binaries are first formed by three-body encounters. While three of them are MS-MS binaries, companions of them evolve to BHs. The BH of the rest binary evolve from a MS in single stellar evolution. All of Group 4 binaries exchange their members with other MSs via binary-single interactions and escape from open clusters. They may have escaped from open clusters at the moment the clusters evaporate.

Binaries in all the Groups have BH masses in a range from $3M_\odot$ to $20M_\odot$. The mass distribution of BHs are very similar among the four Groups.

3.2 BH-MS Binaries Observable with Gaia

In this section, we estimate the number of BH-MS binaries for the following constraints. We first count the number of binaries within 10 kpc from the Sun by taking the lifetime of the MS into account.
account. Then, we also add the effects of interstellar extinction and observational constraints (see sections 2.3.2 and 2.3.3 for more details). Note that we consider only Group 1 and 2 binaries as detectable with Gaia since we adopt a constraint from orbital periods (see section 2.3.3).

Table 1 shows the total expected number of BH-MS binaries within 10 kpc from the Sun and of detectable binaries with Gaia ($N_{\text{det}}$). We also show the respective numbers of Groups 1 and 2 binaries under different restrictions. “10 kpc model” indicates all the binaries within 10 kpc from the Sun (without interstellar extinction and any observational constraints), where $D_{\text{max}} = 10$ kpc in equation (6). “Breivik model” denotes binaries detectable in 3σ confidence level when we take into account only the observational constraint from parallax (described in equation (18) and relax the constraint to 3σ), where $D_{\text{max}} = \min(10, D_p)$ kpc in equation (6). “Yamaguchi model” shows binaries observable, when we take into account interstellar extinction (section 2.3.2) and all the observational constraints (see equations (18) and (19) of section 2.3.3) where $D_{\text{max}} = \min(10, D_{\text{MS}}, D_p, D_a)$ kpc in equation (6).

The total number of BH-MS binaries formed in open clusters within 10 kpc from the Sun is $\sim 2 \times 10^3$. Even if we take into account the most strict restrictions related to interstellar extinction and the observational constraints from parallaxes and orbital separations, we estimate that Gaia can detect $\sim 10$ BH binaries originating from open clusters (see the Yamaguchi model). If we relax the restrictions, we predict that Gaia will be able to observe $\sim 7 \times 10^2$ BH binaries (see the Breivik model).

We find that Group 2 is dominant in all the types of the restrictions. Since binaries in Group 2 have less massive MSs and longer orbital periods, the MSs live longer and the observational constraint from orbital separations does not suppress the number of Group 2 binaries very much.

For the Breivik model, the number of Group 1 binaries does not decrease compared to that for the 10 kpc model. The observational constraint (from parallaxes) for the Breivik model is not as strict as those of the Yamaguchi model. The number of Group 2 binaries becomes one-third of that of the 10 kpc model. This is because MSs of Group 2 binaries are less massive and fainter. On the other hand, the number of Group 1 and 2 binaries in the Yamaguchi model decrease drastically. In particular, the number of Group 1 becomes $10^{-5}$ of that of the Breivik model. Since Group 1 has tighter binaries than Group 2, most of the binaries in Group 1 cannot be observed due to the observational constraint from orbital separations.

Figure 3 shows two-dimensional histogram of BH-MS binaries within 10 kpc from the Sun (the 10 kpc model). Here, we assign the distribution in Figure 1 to each period-mass bin and calculate the number of binaries in each bin. Here, the lifetime of MS of the binaries is considered, but interstellar extinction and any observational constraints have not been included yet.

In this plot, the number of binaries with less massive MSs is larger than that of binaries with more massive MSs despite that the numbers are very similar when they are formed in clusters (see Figure 1). This is because the lifetime of low-mass MS is longer than that of massive MS.

In Figure 4, we present the two-dimensional histogram for the number of binaries detectable with Gaia for the Yamaguchi model. Compared with Figure 3, a significant fraction of binaries in Group 1 and 2 become difficult to observe. In particular, as seen in Table 1, Group 1 binaries are hardly observed because of the observational constraints from parallaxes and orbital separations. Therefore, we expect that BH-MS binaries formed in open clusters should be found in the MS mass-period region of Group 2.

In the following, we describe binary parameter distributions of observable BH-MS binaries. We present the distance distribution of binaries from the Sun in Figure 5. Without observational constraints and interstellar extinction, the number of binaries monotonically increases as we include distant binaries as seen for the 10 kpc model, simply because the integrated volume also increases. For the Breivik model, we find that most of binaries are still observable. For the Yamaguchi model, however, the number of observable BH-MS binaries dramatically drops over a few kpc from the Sun. In addition, no BH binaries farther than $\sim 6$ kpc are observable due to the observational constraint from orbital separations.

We can confirm that the decrease of short-period binaries by considering the observational constraints. In Figure 6, we show the orbital period distribution of each model. For the Yamaguchi model, the number of binaries with short periods ($\lesssim 1.5$ yr) decrease by almost three orders of magnitude, while the number of binaries with long periods ($\gtrsim 1.5$ yr) does only by two orders of magnitude. The gap between $1.75 - 2$ years reflects the fact that no binaries escape from open clusters based...
Fig. 5. The number distribution of BH-MS binaries as a function of the distance from the Sun. Solid histogram shows the number of binaries within 10 kpc from the Sun. Dotted one describes the number considering the observational constraint from parallaxes in 3\(\sigma\) confidence level (the Breivik model), and dashed one shows the number with interstellar extinction and the observational constraints from parallaxes and orbital separations (the Yamaguchi model).

We also investigate the distribution of masses of binaries originating from open clusters. Figure 7 presents the MS mass distribution for each observation model. Without any observational constraints (the 10 kpc model), low-mass MS (\(\lesssim 5M_\odot\)) is the most populous because of the initial mass function and their long lifetimes, and a few tens of BH-MS binaries with a high-mass MS (\(\gtrsim 5M_\odot\)) are predicted. For the Breivik model, the distribution does not change except for the least massive stars. For the Yamaguchi model, only \(\sim 10\) BH-MS binaries with a low-mass MS are detectable with Gaia. In addition, high-mass MS-BH binaries would not be detected. These high-mass MS-BH binaries belong to Group 1 and therefore have a short period. They are hardly observed due to the observational constraint from the orbital separation as described above.

We also present the BH mass distribution expected to be observed in Figure 8. The distribution without observational constraints shows a flat distribution in the range from \(\sim 2.5M_\odot\) to \(\sim 13M_\odot\). This is similar for the Breivik model. For the Yamaguchi model, on the other hand, the most detectable binaries have BHs with mass of \(\sim 10M_\odot\). This can be explained as follows. Fewer binaries with more massive BH than \(\sim 10M_\odot\) exist compared with those with less massive BHs (see the 10 kpc model) because of the initial mass function. On the other hand, BH binaries with more massive BHs can be more easily detected, since they swing around their MS companions more largely. Thus, detectable BH mass distribution using binary observation have a peak at \(\sim 10M_\odot\).

In the eccentricity distribution, we find a characteristic of binaries dynamically formed in open clusters. In Figure 9, we present the eccentricity distribution. In all the observation models, BH-MS binaries tend to have high eccentricities (\(e \gtrsim 0.1\).
Especially in the Yamaguchi model, BH-MS binaries rarely have nearly zero eccentricities. In general, dynamically formed binaries have non-zero eccentricities, and therefore the number of BH-MS binaries with nearly zero eccentricities is initially small. On the other hand, BH-MS binaries which experience common envelope phases have nearly zero eccentricities. However, such binaries tend to be very tight and have too short a period to be observed. Thus, we predict that BH-MS binaries detectable with Gaia tend to be eccentric.

**4 Discussion**

Hereafter, we discuss the differences between BH-MS binaries formed in the MW galactic field and in open clusters. A possible clue can be eccentricities of BH binaries. Figure 4 of Breivik et al. (2017) shows that BH binaries formed in a galactic field prefer nearly zero eccentricities, while those formed in open clusters have high eccentricities at high probability. If a BH binary with a nearly zero eccentricity is discovered, its origin must be a galactic field. If a BH binary with high eccentricity is found, it could be formed on a galactic field or in an open cluster. By comparing the number of BH binaries with eccentricities of \(e \geq 0.1\) in Figure 4 of Breivik et al. (2017) and that of our Breivik model in Figure 9, we can find the numbers of the former and latter are \(\sim 10^3\), comparable. Hence, half of BH binaries with high eccentricities originate from open clusters.

Another possible clue is the chemical abundance pattern of companion stars of BH binaries. As described above, BH binaries originating from open clusters are formed, such that the BH progenitors evolve to BHs, and subsequently they get their final companions. Thus, the BH progenitors do not pollute their final companions. Note that the pollution processes can be stellar wind and (failed) supernova ejecta. On the other hand, BH binaries originating from a galactic field are binaries from the beginning time. Thus, the companions should be polluted by the BH progenitors. In summary, if a companion star in a BH binary has a normal chemical abundance, the BH binary should be formed in open clusters.

As seen in Figure 2 of Breivik et al. (2017), BH binaries formed on a galactic field have a period gap around a period of \(1\) year for the following reason. Binaries with orbital periods of \(\lesssim 1.5\) year at the initial time become shorter-period binaries due to common envelope evolution, while binaries with \(\gtrsim 1.5\) year keep their periods due to the absence of binary interactions. On the other hand, binaries in Group 2 do not have such a period gap. This is because they are formed through both of binary and dynamical interactions (see Figure 2). By comparing cluster-origin BH binaries (our results) with field-origin BH binaries (Breivik’s results), we find BH binaries with orbital periods of \(\sim 1.5\) year and MS masses of \(\lesssim 5M_\odot\) are dominated by cluster-origin ones.

**5 Conclusion**

In this paper, we estimated the number of BH-MS binaries formed in open clusters detectable with Gaia and investigated their properties. We used the results of N-body simulations of open clusters as the properties of binaries produced in them. We assumed that local star-formation rate was proportional to the local stellar density and that the star formation rate in the past was constant. We also assumed that the fraction of stars forming open clusters was constant. By using the results of our simulations and these assumptions, we estimated the parameter distributions of BH-MS binaries formed in open clusters.

The results of N-body simulation indicated that the detectable BH-MS binaries consist of two groups. Group 1 binaries have heavier MS mass \((m_{MS} \gtrsim 5.6M_\odot)\). They are formed through three-body encounters and binary-single encounters when they are still MS-MS binaries. They experience common envelope phases and then one of binary stars evolve to BHs. Their evolution is similar to that of isolated field binaries. Group 2 binaries have less massive MS masses \((m_{MS} \sim 1.8 - 5.6M_\odot)\) than those of Group 1. Most of Group 2 binaries also experience common envelope phases, but they later exchange MSs before escaping from open clusters. These two types of BH-MS binaries can be detected with Gaia.

We estimated \(2.0 \times 10^3\) BH-MS binaries exist within 10 kpc from the Sun. Group 2 binaries are dominant because they have less massive MSs and as a result, they have longer lifetimes.

We also considered the effect of interstellar extinction and the observational constraints following Yamaguchi et al. (2018). By considering these, we predicted that \(\sim 10\) BH-MS binaries can be detected with Gaia and that they are rarely detected further than 6 kpc from the Sun. In particular, Group 1 binaries are hardly detected. They are tighter binaries than those
in Group 2, and therefore the observational constraint from orbital separations makes them much difficult to be detected. Finally, we predicted that BH-MS binaries with less massive MSs ($m_{\text{MS}} \lesssim 5 M_\odot$), longer orbital periods ($P \gtrsim 1.5$ year) and higher eccentricities ($e \gtrsim 0.1$) would be binaries originating from open clusters rather than isolated binaries formed in the MW galactic field.

We found chemical abundance patterns of companion MSs will help us to identify the origin of binaries. Group 2 binaries exchange MSs through binary-single interaction after common envelope phases. Therefore, companion MSs are supposed to have normal chemical abundances. Such binaries are never formed via isolated binary evolution.

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