Revealing Black Holes with *Gaia*

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**Abstract**

We estimate the population of black holes with luminous stellar companions (BH-LCs) in the Milky Way (MW) observable by *Gaia*. We evolve a realistic distribution of BH-LC progenitors from zero-age to the current epoch taking into account relevant physics, including binary stellar evolution, BH-formation physics, and star formation rate, in order to estimate the BH-LC population in the MW today. We predict that *Gaia* will discover between 3800 and 12,000 BH-LCs by the end of its 5 years mission, depending on BH natal kick strength and observability constraints. We find that the overall yield, and distributions of eccentricities and masses of observed BH-LCs, can provide important constraints on the strength of BH natal kicks. *Gaia*-detected BH-LCs are expected to have very different orbital properties compared to those detectable via radio, X-ray, or gravitational-wave observations.

**Key words:** astrometry – Galaxy: stellar content – methods: numerical – methods: statistical – stars: black holes – stars: statistics

**1. Introduction**

Recent discoveries of merging binary black holes (BBHs) by the Laser Interferometer Gravitational-wave Observatory (LIGO)/Virgo collaboration have reignited interest in the formation of stellar-mass black holes (BHs). Stellar-mass BHs are naturally created as the final state of stars with masses in excess of ~10 $M_\odot$. However, discovering these dark remnants remains notoriously hard. The currently employed channels for the discovery of BHs require selective binary architectures. For example, BHs can be detected while accreting at a high-enough rate from a close binary companion via X-ray and radio observations (e.g., McClintock & Remillard 2006; Remillard & McClintock 2006). Otherwise, BHs, in even tighter orbits may emit gravitational-wave (GW) radiation and be observed by GW detectors.

Both methods introduce selection biases and leave completely unattended a vast regime in parameter space of binaries involving at least one BH. Based on the Kroupa (2001) initial stellar mass function (IMF) and stellar mass in the Galaxy, the MW is expected to contain ~10$^5$BHs. Depending on the initial binary fraction of high-mass stars, a large fraction of these BHs are expected to have luminous companions (Sana et al. 2012). Nevertheless, the BlackCAT catalog contains only 59 BH candidates in the MW (and five extragalactic) discovered via X-ray and radio observations (Corral-Santana et al. 2016).

More recently, the LIGO/Virgo observatories have opened a new window through which to observe BHs by detecting GWs from merging BBHs (Abbott et al. 2016a, 2016b, 2017a, 2017b). Estimated theoretical event rates based on four detections and one lower-significance trigger event to date indicate that this channel will yield ~300–800 by the end of the nominal *Gaia* mission (Abbott et al. 2016c, 2017a). However, these events are likely to be dominated by higher-mass and distant BBHs due to selection bias (e.g., Mapelli et al. 2017). Stellar-mass BHs are also expected to be observable with mHz GW frequencies using LISA (Amaro-Seoane et al. 2017). The estimated number of BBHs in the MW observable by the Laser Interferometer Space Antenna (LISA) is ~several dozens (e.g., Nelemans et al. 2001; Belczynski et al. 2010a; Sesana 2016; Christian & Loeb 2017).

*Gaia* provides a new opportunity to hunt for BHs with luminous stellar companions (LCs) in the Milky Way (MW) with orbital properties in a different regime relative to the methods discussed above. We emphasize that the required observations demand no additional resource allocation and come as a “bonus” to the science goals of *Gaia*.

The method of detection, in principle, is very simple. By mission end, *Gaia* will constrain the motions of ~10$^3$ luminous stars in the MW (Gaia Collaboration et al. 2016a). If some of these stars are in close binary orbits with BHs (orbital period comparable to *Gaia* mission length), then the period of the binary and the mass of the BH can be estimated from the stellar motion. As a “proof of concept,” Mashian & Loeb (2017) recently suggested that *Gaia* may be able to detect ~$f \times 10^5$ such BHs over the nominal mission lifetime. Here, $f$ contains several important astrophysical considerations, including distribution of natal kicks to BHs, binary fraction in massive stars, mass-transfer events, and the orientation of these binaries in the MW with respect to us. These astrophysical considerations are crucial in determining the number and properties of black holes with luminous stellar companions (BH-LCs) detectable by *Gaia*.

In this work, we use a detailed population synthesis, taking into account astrophysical processes relevant for the formation of BH-LCs, in order to predict the number and properties of those that *Gaia* will discover. We pay particular attention to how different assumptions for largely uncertain BH-formation physics may affect these results. In Section 2, we describe the setup of our simulations and detail observability cuts applied to our results in order to obtain the *Gaia*-observable population. We show key results from our simulations in Section 3. We conclude and discuss implications of our results in Section 4.

**2. Simulations**

For this study, we consider LCs at any point during their main sequence (MS) or post-MS evolution, as long as they are luminous at the present epoch. We simulate populations of
binaries with at least one massive star, the BH progenitor, from zero-age to the present epoch of the MW and collect the BH-LC binaries at present. We model both the thin and thick disks in the MW using our binary population synthesis code, COSMIC, which uses BSE to evolve binaries (Hurley et al. 2002). We have updated BSE to incorporate our latest understanding of stellar winds from high-mass stars (Vink et al. 2001; Vink & de Koter 2005; Belczynski et al. 2010b), and natal kicks to BHs (Fryer et al. 2012). We also include core-mass dependent stellar envelope binding energies in our common envelope evolution prescription (Xu & Li 2010). See Rodríguez et al. (2016) for a detailed description of all of the improvements.

We initialize binary populations for the MW thin and thick disks using standard assumptions. We assume a Kroupa (2001) IMF between 0.1 and 100 $M_\odot$ for primary masses in both the thin and thick disks. Mass ratios are sampled uniformly between 0.001 and 1 (Mazeh et al. 1992; Goldberg & Mazeh 1994). We assume a primary-mass-dependent binary fraction proportional to $1/2 + 1/4 (\log m)$ (van Haften et al. 2013). We distribute the orbital separations uniformly in log-space up to $5.75 \times 10^6 R_\odot$ and as $(a/10\,\odot)^{1/2}$ below $10 R_\odot$ (Han 1998). We assume a thermal eccentricity distribution (Heggie 1975).

We assume a constant star formation rate (SFR) of $2.15 \, M_\odot\, yr^{-1}$ over 10 Gyr for the thin disk producing a total mass of $M_{\text{thin}} = 2.15 \times 10^{10} M_\odot$ and a single burst of star formation 11 Gyr ago for the thick disk producing a total mass of $M_{\text{thick}} = 2.6 \times 10^{10} M_\odot$ (Robin et al. 2003). We assign metallicity $Z = Z_\odot$ and 0.15$Z_\odot$ for the thin and thick disks, respectively (Yoshii 2013).

2.1. Natal Kicks to BHs

The strength of BH natal kicks is uncertain, but is expected to be related to neutron star (NS) natal kicks. Detailed modeling of Galactic scale heights of individual observed BH X-ray binaries (XRB) suggest wide ranges in kick magnitudes. Similar modeling for Galactic scale heights of observed BH XRBs as a population indicates natal kicks of $\sim 100 \, km \, s^{-1}$ (Repetto et al. 2017, and references therein). Depending on the orientation and magnitude of the natal kick, the orbital eccentricity may increase, decrease, or the binary may become unbound altogether. As the detectability of a BH-LC using Gaia crucially depends on the sky-projected size of its orbit, BH natal kicks are expected to affect Gaia’s detectability of BH-LCs.

To this end, we simulate three sets of models using BH natal kick prescriptions bracketing possibilities in nature: zero natal kicks (Zero-kick), NS kicks modulated by fallback of mass onto the BH (FB-kick), and full NS kicks (NS-kick). Natal kicks are randomly oriented and NS natal kicks are drawn from a Maxwellian distribution with $\sigma = 265 \, km \, s^{-1}$ (Hobbs et al. 2005).

We break the simulation into three components: fixed population, Galactic realizations, and observational cuts. The fixed population describes the distributions of binary properties resulting from population synthesis adopting a specific binary evolution model and star formation history. Galactic realizations are created by sampling from the fixed population, where each binary sample is also assigned a Galactic position and orientation. Finally, observational cuts are placed on the Galactic population in order to determine which BH-LCs are detectable by Gaia. We detail each step below.

2.2. Fixed Population

The fixed population encapsulates the full range of binary parameters resulting from a population synthesis using a given binary evolution model, BH-formation physics, and star formation history; e.g., we generate a fixed population for the thin disk evolved with the FB-kick model. Our full suite of simulations results in six fixed populations: three kick models each for the thin and thick disk populations.

In order to ensure that convergence is achieved even for the low-probability regions of the parameter space, we employ a match criteria that compares the normalized histograms of binary parameters between consecutively and cumulatively simulated populations. The match is computed bin by bin and summed over the entire parameter range as

$$\text{match} = \frac{\sum_{i=1}^{N} P_{k,i} P_{k,i+1}}{\sqrt{\sum_{i=1}^{N} (P_{k,i} P_{k,i+1})}},$$

where $P_{k,i}$ denotes the probability for the $i$th bin for the $i$th iteration.

As the number of simulated binaries increases, the match tends to unity. We continue to run simulations until match $> 0.999$. For this study, we compute the match for the binary masses ($M_{\text{BH}}, M_{\text{LC}}$), orbital period ($P_{\text{orb}}$), eccentricity (Ecc), LC temperature ($T_{\text{LC}}$), and LC luminosity ($L_{\text{LC}}$).

While generating the fixed population, we log the total sampled mass, including single stars, as well as birth and death rates of BH-LC binaries. From these rates, we compute the total number of BH-LC binaries, $N_{\text{BH-LC}}$, at present in each Galactic component by normalizing the total sampled mass of our fixed population to the total mass of the Galactic component.

2.3. Galactic Realizations

We generate a six-dimensional kernel density estimate (KDE) from the fixed population using parameters of interest ($M_{\text{BH}}, M_{\text{LC}}, P_{\text{orb}}, E, T_{\text{LC}}, L_{\text{LC}}$). We sample binaries from this KDE and assign Galactocentric three-dimensional positions ($x_{\text{Ga}}, y_{\text{Ga}}, z_{\text{Ga}}$). The positions are drawn from simple spatial distribution functions representing the distribution of stars in the MW (Yu & Jeffery 2015). For the thin disk, we assume all of the binaries are distributed with an exponential radial ($R$) fall-off and a hyperbolic secant dependence in the vertical direction ($z$)

$$\rho(R, z) \propto \exp^{-R/R_{\text{thin}}} \sech^2(-z/z_{\text{thin}}),$$

where $R_{\text{thin}} = 2.5 \, kpc$ and $z_{\text{thin}} = 0.352 \, kpc$. For the thick disk we assume an exponential radial and vertical fall-off

$$\rho(R, z) \propto \exp^{-R/R_{\text{thick}}} \exp^{-z/z_{\text{thick}}},$$

with $R_{\text{thick}} = 2.5 \, kpc$ and $z_{\text{thick}} = 1.158 \, kpc$. In both cases, we assume azimuthal symmetry with $\phi$ sampled uniformly between $[0, 2\pi]$. We compute the heliocentric distance to each binary by assuming a solar position of $R = 8.5 \, kpc$, $\phi = 0.0$, and $z = 20 \, pc$ (Yoshii 2013).

We randomly orient each binary with respect to a fixed observer by sampling inclinations ($i$) uniformly in $\cos(i)$
between \([-1, 1]\), and argument of periapsis (\(\omega\)) and longitude of ascending node (\(\Omega\)) uniformly between [0, \(2\pi\)].

We repeat the process detailed above to generate 500 Galactic realizations per model/star formation in order to explore variance in the Gaia-observable BH-LC population.

### 2.4. Observability Cuts

We considered limiting magnitudes of \(G = 12–20\) based on expected Gaia performance. We compute visual magnitudes, \(m_v\), and \(B - V\) colors from the bolometric corrections in Flower (1996) and Torres (2010) using \(L_{LC}\) and \(T_{LC}\). We compute Gaia \(G\) magnitude using the color–color transformations of Jordi et al. (2010).

We conservatively require observation of a full orbit during the Gaia mission lifetime, thus placing a hard upper limit \(P_{\text{orb}} \leq 5\) years. We place a lower limit on the astrometric signature

\[
\alpha = \left( \frac{a_{\text{LC,project}}}{\text{au}} \right) \left( \frac{d}{\text{pc}} \right)^{-1} \text{arcsec},
\]

based on the projected size of the LC orbit \(a_{\text{LC,project}}\), such that \(\alpha\) is greater than Gaia’s magnitude-dependent astrometric precision, \(\sigma_G(G)\) (Gaia Collaboration et al. 2016b). We estimate optimistic (pessimistic) yields using \(\alpha \geq \sigma_G(3\sigma_G)\). Binary separation is defined as \(a = a_{\text{LC}} + a_{\text{BH}} = a_{\text{LC}}(1 + M_{\text{LC}}/M_{\text{BH}})\). Projected separation is computed with orbital parameters: \(i\), \(\Omega\), and \(\omega\) using the Thiele-Innes elements

\[
\begin{align*}
A &= a_{\text{LC}} \cos \omega \cos \Omega - \sin \omega \sin \Omega \cos i, \\
B &= a_{\text{LC}} \cos \omega \sin \Omega + \sin \omega \cos \Omega \cos i, \\
F &= a_{\text{LC}} (-\sin \omega \cos \Omega - \cos \omega \sin \Omega \cos i), \\
G &= a_{\text{LC}} (-\sin \omega \sin \Omega + \cos \omega \cos \Omega \cos i).
\end{align*}
\]

The projected cartesian components \(x_{\text{project}}\) and \(y_{\text{project}}\) are:

\[
\begin{align*}
x_{\text{project}} &= AX + FY, \\
y_{\text{project}} &= BX + GY,
\end{align*}
\]

where \(X = \cos E - \text{Ecc}\) and \(Y = \sqrt{1 - \text{Ecc}^2} \sin E\). The projected orbital separation, \(a_{\text{LC,project}}\) is the semimajor axis of the projected ellipse.

Figure 1 shows an illustration of these projection effects for a sample BH-LC. In this example, \(M_{\text{BH}} = 10 M_\odot\), \(M_{\text{LC}} = 5 M_\odot\), eccentricity \(\text{Ecc} = 0.6\), \(P_{\text{orb}} = 4\) years, and, \(a_{\text{LC}} = 18.64\) au. The projected separation, after transforming as in Equations (9) and (10) is \(a_{\text{LC,project}} = 15.28\) au.

### 3. Results

#### 3.1. Full BH-LC Population

We consider first the overall population of BH-LCs at present, without observability cuts. This population represents the full range of BH-LC binaries potentially produced in the MW for each of our models. Figure 2 shows distributions of LC mass and orbital period of all of the BH-LC binaries from our simulations for BH-LCs containing both MS and post-MS stars. Light blue bands and blue lines show the general regions where BH-LCs may be observable by LISA and X-ray observations, respectively, while yellow dashed lines and bands show the region of orbital periods roughly observable by Gaia, with an illustrative lower limit placed at \(P_{\text{orb}} \approx 0.5\) day.

The lower limit represents the average minimum orbital period observable by Gaia from our optimistic models. The majority of BH-LCs with \(P_{\text{orb}} \approx 5\) years lie in the Gaia-observable region. Only \(\approx 1\%\) BH-LC systems in the thin disk with \(P_{\text{orb}} \approx 5\) years also have \(P_{\text{orb}} < 0.5\) day, while \(\approx 11\%\) of thick-disk BH-LCs with \(P_{\text{orb}} \approx 5\) years have \(P_{\text{orb}} < 0.5\) day. Thus Gaia will provide an important probe into the BH-LC parameter space that is complementary and otherwise inaccessible to radio, X-ray, and GW observations.

Note that BH-LCs with \(P_{\text{orb}} \geq 10^5\) years would likely be disrupted due to Galactic tides and appear in our full population (Figure 2) only because we did not take this into account. This does not affect our results for the Gaia-detectable BH-LCs, because those are tightly bound and are unlikely to be disrupted unless placed in very dense environments near the Galactic center.

The number of BH-LCs decreases with increasing natal kick magnitudes, as larger kicks disrupt a larger fraction of primordial binaries. For the same reason, natal kicks also affect the distribution of \(P_{\text{orb}}\) of BH-LCs. While BH-LCs are disrupted in the Zero-kick model only if the change in mass during BH formation is severe enough to reduce the orbital binding energy to the point of unbinding, the NS-kick model leads to disruption of BH-LC progenitors with \(P_{\text{orb}} \geq 5\) years.

We find a significant population of BH-LCs with \(P_{\text{orb}}\) longer than the nominal Gaia mission in all of the models except the NS-kick model. This population exclusively contains BH-LCs that have not experienced a common envelope evolution. The population with orbital periods in the Gaia-observable range and lower contain BH-LCs that have experienced a common envelope, as well as BH-LCs that have not. Our NS-kick model does not allow formation of BH-LCs with \(P_{\text{orb}} \geq 5\) years and \(M_{\text{LC}} \leq 0.25 M_\odot\), while other models with lower natal kicks allow formation of these systems (Figure 2). By extending the Gaia mission beyond the nominal 5 years, our \(P_{\text{orb}} \leq 5\) years condition could be relaxed, and Gaia may constrain highly
uncertain BH natal kicks from the properties of detected BH-LCs at longer orbital periods.

3.2. Gaia-observable Population

Figure 3 shows the number of systems observable by Gaia ($N_{\text{obs}}$) as a function of limiting $G$ magnitude. The number of observable systems is inversely related to the BH natal kick strength because the likelihood of unbinding a BH-LC progenitor increases with kick strength.

Table 1 shows the result of our astrometric cuts. The total number of BH-LCs formed in our models is roughly consistent with the estimates in Mashian & Loeb (2017). However, the majority of the systems formed lie above our upper $P_{\text{orb}}$ cut (Figure 2). In addition to the natal kick prescription, the Galactic component has a noticeable effect on the number of BH-LC systems. Because the thick disk is modeled as a single star burst 11 Gyr ago, all of the LCs in the thick disk at present are low mass. Large natal kicks for BHs such as our NS-kick model affect BH-LCs with low-mass LCs more (Figure 2; Section 3.1). As a result, in the thick disk, the NS-kick model yields a very low $N_{\text{obs}}$. The adopted continuous SFR in the thin disk keeps $N_{\text{obs}}$ relatively high even for the NS-kick model by forming high-mass luminous stars very close to the present epoch.

We estimate 3800–12,000 BH-LCs in the MW are detectable by Gaia depending on adopted BH natal kick strengths and demand of the astrometric cut. Considering all of the cases, we predict at least $10^3$ BH-LCs observable by Gaia.

Note that carefully considering astrophysics and Gaia’s selection biases in our study has reduced the predicted yield by a factor of $\sim 10^{-2}$ relative to the prediction by Mashian & Loeb (2017). Still, our predicted yield is nearly two orders of magnitude higher than the number of BH binaries already known. Thus, Gaia observations could dramatically improve our understanding of BHs and BH binaries in particular.

![Figure 2](image_url) Two-dimensional probability dimension functions (PDFs) for all of the BH-LCs in the MW in the LC-mass vs. orbital period plane. The top and bottom rows show distributions for the thin and thick disk, respectively. Columns (a)–(c) show Zero-kick, FB-kick, and NS-kick models, respectively. Light blue bands show the spread of orbital periods observable by LISA. Blue lines represent an approximate upper limit for accreting BHs via Roche-lobe overflow (estimated using $M_{\text{BH}} \approx 36 M_\odot$, the most massive BH created in our models). Yellow bands bounded by dotted lines show the Gaia-observable range, spanning $P_{\text{orb}} \approx 0.5$ day to 5 years.

![Figure 3](image_url) Mean number of observable BH-LCs as a function of limiting $G$ magnitude computed from 500 Galactic realizations. Shades show 3σ regions above and below the mean denoted by the lines. Dashed (solid) lines denote our estimates using pessimistic (optimistic) astrometric cuts (Section 2.4). Blue, red, and black shading denote Zero-kick, FB-kick, and NS-kick models, respectively.

### Table 1

| Model   | Component | Total Obs. | Opt. Obs. | Pess. Obs. |
|---------|-----------|------------|-----------|------------|
| Zero-kick | Thin disk | 475840     | 9120      | 5145       |
|         | Thick disk| 28197      | 2708      | 1159       |
| FB-kick  | Thin disk | 250707     | 4632      | 2786       |
|         | Thick disk| 12523      | 2918      | 1170       |
| NS-kick  | Thin disk | 71653      | 4823      | 3249       |
|         | Thick disk| 6561       | 1283      | 480        |
3.3. Observable BH-LC Parameters

Magnitude $G$, $\alpha$ (Equation (4)), and $P_{\text{orb}}$ will be directly observed for a Gaia-detected BH-LC, while binary masses and Ecc can be inferred via modeling. Figure 4 shows distributions of these properties for observable BH-LCs in our models.

Distributions of $\alpha$, $G$, and $P_{\text{orb}}$, are governed primarily by the hard requirements on $\alpha$ and $P_{\text{orb}}$ that we impose for detectability, and our adopted primordial IMF and binary properties (Section 2). Distributions of Ecc, $M_{\text{BH}}$, and $M_{\text{LC}}$ exhibit differences depending on the adopted BH-formation physics.

Most notable is the rise in the number of systems with Ecc $> 0.9$ for the FB-kick and NS-kick models, while the Zero-kick model flattens at high eccentricities. This is a direct outcome of eccentricity excitation by SN kicks to BHs. Independent of the BH-physics model, a high fraction of detectable BH-LCs have high eccentricities. Thus, the effects of eccentricities on the sky-projected size of a binary (Figure 1) must be taken into account in order to correctly interpret astrometric observations of BH-LCs.

Mass distributions also vary to some degree from model to model. The NS-kick model shows a dearth of BHs with masses between $15 M_\odot$ and $25 M_\odot$ relative to the Zero-kick and FB-kick models. In this range BHs receive zero or little natal kicks for the Zero-kick and FB-kick models, respectively, whereas the BHs in the NS-kick model receive large natal kicks (Fryer et al. 2012). The $M_{\text{LC}}$ distribution is affected similarly between $5 M_\odot$ and $20 M_\odot$, where models with larger natal kicks show fewer observable BH-LCs as a result of binary disruptions during BH formation. We do not expect the peak at $M_{\text{LC}} \approx 40 M_\odot$ in the Zero-kick model to be an observable feature in a future Gaia BH-LC catalog. It is caused by a single outlier system in the Zero-kick fixed population that is exceptionally bright due to its mass. This system propagates into our observable synthetic data set during the Galactic realization sample, and is always deemed observable based on the bright LC and orbital period near 5 years.

Admittedly, deriving masses and eccentricities with the observation of only $\alpha$, $G$, and $P_{\text{orb}}$ is difficult. However, Gaia will provide low-resolution spectral energy distributions in red and blue for all observed LCs as well as radial velocities for LCs brighter than $G = 17$ (Jordi et al. 2010). Combining these observations with astrometric information may allow parameterization of the binary, including minimum-mass measurements of the BH. Such modeling will be the topic of a future study.

4. Discussion

In this study we have predicted that Gaia will potentially observe $10^3$–$10^4$ BH-LCs in the MW depending on BH natal kick physics and observational constraints. These observations could increase the number of known BHs by two orders of magnitude in less than 5 years. Moreover, the properties of the BH-LCs that Gaia will detect occupy a different regime from those detectable via currently employed methods (Figure 2).

We have used a detailed population synthesis in order to show the effects of BH natal kicks on the Galactic BH-LC population. The number of observed systems places the strongest constraint on the natal kicks BHs receive: the number of observable BH-LCs decreases with increasing natal kick strength (Figure 3). Moreover, we find that distributions of eccentricity and masses of observable BH-LCs may also help constrain natal kick physics, especially if Gaia’s mission length is extended (Figures 2 and 4).

We predict far fewer observable BH-LC systems than the $2 \times 10^7$ predicted by Mashian & Loeb (2017), suggesting that the fraction of BH-LC progenitors that survive to the present is low ($f \sim 0.01$). In spite of this, Gaia promises to discover at least $10^3$ BH-LCs.
A large fraction of LCs in the observed BH-LC population will evolve into compact objects. Thus, connections may be drawn between the Gaia-observable population and the X-ray or GW-observable populations. Thus, BH-LCs observable by Gaia provide a unique opportunity to probe the population of stellar-mass BHs.

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