Tidal capture formation of Low Mass X-Ray Binaries from wide binaries in the field

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ABSTRACT

We present a potentially efficient dynamical formation scenario for Low Mass X-ray Binaries (LMXBs) in the field, focusing on black-hole (BH) LMXBs. In this formation channel LMXBs are formed from wide binaries (> 1000 AU) with a BH component and a stellar companion. The wide binary is perturbed by fly-by’s of field stars and its orbit random-walks and changes over time. This diffusion process can drive the binary into a sufficiently eccentric orbit such that the binary components tidally interact at peri-center and the binary evolves to become a short period binary, which eventually evolves into an LMXB. The formation rate of LMXBs through this channel mostly depends on the number of such BH wide binaries progenitors, which in turn depends on the velocity kicks imparted to BHs (or NSs) at birth. We consider several models for the formation and survival of such wide binaries, and calculate the LMXB formation rates for each model. We find that models where BHs form through direct collapse with no/little natal kicks can give rise to high formation rates comparable with those inferred from observations. This formation scenario had several observational signatures: (1) the number density of LMXBs generally follows the background stellar density and (2) the mass function of the BH stellar companion should be comparable to the mass function of the background stellar population, likely peaking at $0.4$ $- 0.6$ $M_\odot$. The latter aspect, in particular, is unique to this model compared with previously suggested LMXB formation models following common envelope binary stellar evolution. We note that NS LMXBs can similarly form from wide binaries, but their formation rate through this channel is likely significantly smaller due to their much higher natal kicks.

Key words: keyword1 – keyword2 – keyword3

1 INTRODUCTION

Low Mass X-ray Binaries (LMXBs) are binaries composed of a compact object (CO; Neutron star; NS; or a black hole; BH) accreting from a lower mass, typically main sequence (MS) stellar companion with $M_* < 2M_\odot$. The CO accretes through an accretion disc that generates X-ray emission (see Portegies Zwart et al. (1997); Tauris & van den Heuvel (2006); Li (2015) for overviews). Most LMXBs are found in the field, but ~ 10% (Irwin 2005) are found in globular cluster (GC). Given that only ~ 0.1% of stars reside in GCs, this result suggests that the environment of GCs is highly conducive to the formation of LMXBs. It is thought that close encounters in GCs give rise to tidal capture of stars by COs, and the high formation rate of LMXBs. However, the origin of field LMXBs is still debated, as binary stellar evolution models encounter various challenges in producing LMXBs, and in particular formation of BH LMXBs (Eggleton & Verbunt 1986; Kalogera & Webbink 1996, 1998; Kalogera 1998; Ivanova et al. 2006, 2010), where

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(2007) suggested they may form through tidal capture processes similar to those occurring in GCs, at least in the inner dense region of galaxies; this, however, may not apply to most LMXBs outside the inner dense regions of galaxies. Here we suggest a novel scenario in which field LMXB could originate from very wide binary progenitors (semi-major axis $a > 1000$ AU), each composed of a CO and a low mass MS star. Such wide binaries can be perturbed by encounters with field stars and be excited into highly eccentric orbits. A sufficiently high eccentricity can then give rise to a close peri-center approach of the companion star of the CO, resulting in a tidal interaction and the formation of a compact binary LMXB, somewhat similar to the tidal capture formation of LMXBs in GCs. This approach follows the recent study by Kaib & Raymond (2014) who showed that the components of wide main sequence stellar binaries in the field could have high rates of collisions/mergers through such a process.

Motivated by this approach we calculated the formation rates of LMXBs in the field from such processes. We find that under plausible conditions this formation channel could explain the population of field LMXBs, and in particular BH LMXBs, as well as give rise to unique predictions about their properties.

This paper is organized as follows. In section 2 we present the theory for the formation of a LMXB from a wide binary. In section 3 we specify the main channels of formation, and present the expected formation rate in the Galactic disk. In section 4 we discuss the results and summarize.

2 FORMATION OF LMXBS FROM WIDE BINARIES

2.1 Basic Formation Scenario

Let us consider a wide binary, $a > 10^3$ AU, with a stellar mass BH or NS primary and a MS stellar companion. The system is affected by two different perturbations. First, the galactic tide by the host galaxy and in our case is the Milky Way (MW). Second, short duration dynamical interactions with field stars. Here we focus on the latter, likely stronger effect. The dynamical encounters can typically be modeled through the impulse approximation, i.e. in the regime where the interaction time is much shorter than the orbital period time. These perturbations can torque the system, change the orbital angular momentum, and exchange orbital energy thereby decreasing/increasing the binary semi-major axis $a$. If such effects drive the system to a sufficiently small peri-astron passage, $q$, tidal effects on the MS star become important. Such tides can potentially produce significant dissipation even during a single close approach and drive the binary into a short period orbit, as suggested to occur in tidal capture scenarios in dense stellar systems. The small separation between the CO and the MS can then lead to a Roche lobe overflow (RLOF) on the compact object, and consequently produce a LMXB.

2.2 Analytic Description

In this section we derive the formation rate of LMXBs from wide, $a > 10^3$ AU, binary systems. The derivation follows the same approach as Kaib & Raymond (2014) and Hills (1981), however, here we consider the applications and implications for the formation of LMXBs; we refer the reader to these papers for additional details. Here we briefly review the calculation, highlighting the main points and the minor differences arising from the consideration of non equal-mass binaries.

Consider an ensemble of isotropic wide binaries, each consisting of a MS star with mass $m_*$ and radius $R_*$ and a CO with mass $m_{CO}$. The binaries are assumed to have the same SMA, with a thermal distribution of eccentricities ($f(e)de = 2e de$). We derive the probability of forming LMXBs from this ensemble and find its dependence on the SMA of the binaries, $a$. Kaib & Raymond (2014) showed that for MS-MS wide binary, tidal circularization becomes important for pericenter approaches below the tidal barrier $q_T, q_T \approx 5R_*$. For our CO-MS case we need to correct this tidal barrier. First, we assume that no tidal forces act on the CO star (which radius is negligible in this context), which decreases the tidal dissipation effect by a factor of 1/2. Second, we need to account for the change in the tidal force due to the change of $m_*$ to $m_{CO}$, this gives rise to additional a factor of $\alpha \equiv m_{CO}/m_*$. Combining the two factors gives:

$$q_T \approx 5R_* \cdot \frac{1}{2} \cdot \frac{m_{CO}}{m_*} = 5R_* \cdot \frac{1}{2} \cdot \alpha. \quad (2)$$

Orbits which periastron becomes equal to or smaller than $q_T$ will circularize/tidally disrupt or collide with the CO and no longer be wide binaries; such orbits are termed loss cone orbits. The fraction of orbits occupying the lose cone for thermalized ensemble is

$$F_\theta = \frac{5R_*}{a} \cdot \alpha. \quad (3)$$

After one orbital period, all wide binaries with loss-cone orbits are “destroyed” (in the sense that they are no longer wide binaries) as they approach pericenter. Other binaries outside the loss-cone can be perturbed as to change their angular momentum and replenish the loss cone. The average size of the phase-space region into which stars are perturbed during a single orbital period is termed the smear cone, defined by

$$\theta = \frac{\langle \Delta v \rangle}{v_b} \quad (4)$$

where $v_b$ is the binary MS companion velocity for a distance of 1.5a with SMA of $a$, and $\langle \Delta v \rangle$ is the average change in the velocity over an orbital period due to perturbations (Hills 1981). Let us consider fly-by interactions using the impulse approximation, where the interaction is considered to be in the impulsive regime for which the interaction time, $t_{int}$, is much shorter than the binary period, $t_{int} \ll P$. Hills shows that on average the velocity change (for a binary with SMA, $a$), to the binary components is of the order of

$$\langle \Delta v \rangle \approx \frac{3Gm_*}{v_b^2} \quad (5)$$

where $v_*$ is the velocity of the fly-by star with respect to the binary center of mass and $b$ is the closest approach distance of a fly-by (for the complete derivation see Hills 1981). In
Kaib and Raymond’s calculation \( v_b = (G\mu/3a)^{1/2} \) where \( \mu \) is the reduced mass of the binary. In our case the binary is composed of two different mass components and we get

\[
v_b = \left( \frac{G\mu_a}{3a} \right)^{1/2}.
\]

Hence the angular size of the smear cone cause by the impulse of the fly-by on the binary is

\[
\theta = \frac{3\pi G\mu_a}{v_b b^2} \left( \frac{3a}{G\mu} \right)^{1/2} = \frac{9}{4} \frac{m_b}{\mu_a} \frac{v_b}{v_a} \left( \frac{a}{b} \right)^2
\]

and for \( \theta \ll 1 \) we get the fractional size of the smear-cone over the 4\pi sphere to be

\[
F_s = \frac{\pi \theta^2}{4 \pi} = \frac{27}{4} \left( \frac{m_a}{\mu} \right)^2 \left( \frac{G\mu_a}{R_a v_a^2} \right) \left( \frac{a}{b} \right)^4 = 1.
\]

The only difference between our expression and the one presented in Kaib & Raymond (2014) and Hills (1981) is a factor of \( 1/\alpha \).

The condition for the loss cone to be continuously full is that the sizes of the lose cone and the smear cone be equal, i.e. the loss-cone orbits are replenished at least as fast as they are depleted due to the tidal interactions at peri-center. This equilibrium occurs when

\[
F_e = \frac{F_q}{P} = \frac{G M_b}{4 \pi^2 a^3} \left( \frac{G\mu_a}{R_a v_a^2} \right)^{1/2}
\]

where \( M_b = m_{CO} + m_\ast \) is the mass of the binary and \( P \) is the period of the binary. Note that the loss rate is independent of the stellar density in the field, i.e. once the stellar density is sufficiently large as to fill the loss-cone, the loss rate is saturated, and becomes independent of the perturbation rate. Furthermore, one can see from Eq. (10) that the full loss-cone rate scales like \( \dot{L} \propto a^{-3/2} \), i.e. the full loss-cone rate decreases with increasing SMA. As one goes to smaller SMAs, the loss rate increases until it approaches \( F_s/F_q \rightarrow 1 \), at which point the loss-cone is no longer full. At this regime, the empty loss cone regime, the rate is not determined by the size of the loss cone, but by the rate in which binaries are perturbed into the loss-cone. Hence in order to calculate the loss rate in the empty loss cone regime we need to estimate the rate of encounters. We can express the rate of flyby encounters by

\[
f = n_\ast \sigma v\label{eq:f}
\]

where \( n_\ast \) is the stellar density, \( \sigma = \pi b^2 \) is the geometric cross-section and \( v \) is the velocity of the fly-by’s. Given the stellar density, \( n_\ast \) we need to find an expression for the geometric cross-section and the velocity. Eq. (9) gives us the condition for the crossover from the full to empty loss cone regime. Equating Eq. (9) to unity we find the condition

\[
(v, b) = \frac{1}{\alpha} \left( \frac{27}{4} \left( \frac{m_a}{\mu} \right)^2 \left( \frac{G\mu_a}{R_a} \right) \right),
\]

and the the rate \( f \) is given by

\[
f = n_\ast \frac{1}{\alpha} \frac{m_\ast}{\mu} \sqrt{\frac{27 G M_b a^3}{20 R_a}}
\]

Note that the loss rate of binaries increases with \( f \) only until it reaches the orbital frequency. Beyond this point we are in the full loss-cone regime and the loss rate saturates and remains constant.

Combining these considerations together, one can see that at small separations the loss-rate is determined by the empty loss-cone and increases with the binary SMA, until we reach a critical SMA, \( a_{crit} \), at which the loss cone becomes full, and the loss rate is determined by the full loss-cone, and now decreases with larger SMAs. The maximal rate is therefore obtained for binaries with the critical SMA. To compute \( a_{crit} \) we equate \( f \) with the orbital frequency, \( f = (G M_b/4 \pi^2 a^3)^{1/2} \) and solve for \( a_{crit} \):

\[
a_{crit} = \left[ \frac{5 \sigma \mu M_b R_a}{2 \pi^4 m_\ast^2 n_b^2} \right]^{1/7}
\]

which differs from Kaib & Raymond (2014) by a factor of \( 2^\omega \), i.e. for binaries with more massive compact object, the empty loss cone regime becomes more important as the \( a_{crit} \) value is larger.

The loss probability is calculated differently for the two different regimes. For the empty loss cone regime the limiting factor is the value of the function \( f \). \( F_q \) is the fraction of wide binaries destroyed, and therefore \( (1 - F_q) \) represents the fraction of binaries that survive as wide binaries at the relevant timescale. For the full loss cone regime the relevant timescale is \( 1/f \); for the empty loss cone regime the relevant timescale is \( P \). Therefore, this term is a monotonically decreasing function of time, and the probability for a wide binary to closely interact at peri-center and no longer survive as a wide binary is

\[
L_{a < a_{crit}} = 1 - (1 - F_q)^{-f}
\]

where \( t \) is the time since birth of the binary. As one can expect the probability only depends on the size of the loss cone and the rate of interactions. For the limit of \( t \cdot f \cdot F_q \ll 1 \) we can expand eq. (15) and take the leading term, to find the loss probability to be approximated by

\[
L_{a < a_{crit}} = t \cdot f \cdot F_q
\]

Substituting the function \( f \) from eq. (13) and the value \( F_q \) from eq.(3) we then get

\[
L_{a < a_{crit}} = t \cdot n_\ast \cdot m_\ast \cdot a \sqrt{\frac{135 \pi^2 a}{4 \mu}} \sqrt{\frac{G R_e}{\mu}}
\]

Note that there is no \( a \) dependence in this case, and the probability differs from that obtained by Kaib & Raymond (2014) only by a numerical factor.

For the full loss cone regime the limiting factor is not the value of \( f \), but rather the orbital period and/or the orbital frequency. Therefore, the full expression for the loss probability for \( a > a_{crit} \) is

\[
L_{a > a_{crit}} = 1 - (1 - F_q)^{-P/f}
\]

For the limit \( F_q \cdot t/P \ll 1 \) we can approximate the probability by

\[
L_{a > a_{crit}} = t \cdot F_q \cdot \frac{1}{P} = t \cdot a \cdot \sqrt{\frac{256 G M_b R_a^2}{4 \pi^2 a^5}}
\]
where the probability is increased by a factor of $\alpha$ in this case.

The above calculations provide the estimated rates for a simplified scenario, where binaries are randomly perturbed and continue to evolve until they produce LMXBs when their components have close interactions. In reality, the perturbations may also “ionize” a binary and destroy it, namely, the binary is disrupted by the random fly-by’s. Such ionization process decreases the available number of wide binaries, and consequently lowers the rates of LMXBs formation. To account for the ionization process we consider the finite lifetime of wide binaries due to flybys using the approximate relation given by Bahcall et al. (1985) for $t_{1/2}$, the half-life time of a wide binary evolving through encounters

$$t_{1/2} = 0.00233 \frac{a_a}{G m_a n_a}. \quad (20)$$

Taking this into account we can correct for eq. (17) and eq. (19) to get

$$L_{a<a_{crit}} = \tau \cdot n_a \cdot \int a a \left( \frac{135 \pi^2 G R_e}{4 \mu} \cdot 1 - e^{-t/r} \right)$$

and

$$L_{a>a_{crit}} = \tau \cdot \cdot \left( \frac{25 G M_a R_e^2}{4 \pi^2 a^5} \cdot 1 - e^{-t/r} \right),$$

where $\tau = t_{1/2} / \ln 2$ is the mean lifetime of the binary.

### 2.2.1 LMXB formation rate dependence on stellar density

Using the above model to calculate the probability for close interactions leading to LMXB formation we can now derive an overall estimate for the formation rate of LMXBs, by considering realistic distributions for the initial conditions for the wide binaries population and stellar number densities. In order to do so we need to integrate the loss probabilities weighted by the SMA distribution of wide binaries for all SMA in the binaries ensemble. We assume that the SMA distribution of wide binaries follows a log-uniform distribution in $a$, namely $f_a \sim 1/a$, where $f_a$ is the SMA distribution of the wide binaries population (Duchêne & Kraus 2013). We consider binaries in the range from $a_{min} = 10^3 AU$ up to $a_{max} = 3 \cdot 10^4 AU$, where the maximal value is due to cutoff by the Galactic tide.

This estimated rate mostly depends on $a_{crit}$. The values of $a_{crit}$ can be divided to two distinct regimes: the empty cone which scales like the stellar density $n_a$ and the full cone regimes which is constant in $n_a$. For the expression of $a_{crit}$ in eq. (14) we find that there exists a value of $n_a = n_{a0}$ for which $a_{crit} = a_{max}$. This implies that for a given stellar density satisfying $n_a < n_{a0}$ the ensemble is always in the empty loss cone regime and therefore the probability scales like $n_a$ and the number of formed LMXB systems scales like $n_a^2$. This argument neglects the ionization process described earlier. Binary ionization changes the scaling. Following (21), we can write the equation explicitly to get

$$L_{empty} = \frac{0.00233 \cdot \cdot a \cdot \cdot \cdot 135 \pi^2 G R_e}{4 \mu} \left( 1 - e^{-t/r} \right)$$

and

$$L_{empty} \propto \sqrt{ \frac{135 \pi^2 G R_e}{4 \mu} \cdot 1 - e^{-t/r} },$$

which has no density dependence. In our case it should be noted that typically $t \gg \tau$ for the wide binaries we consider. We therefore conclude that once ionization is accounted for, the formation probability of LMXBs in this regime is density independent. To obtain the total formation rates we therefore only need to multiply the probability for LMXB formation per system by the total number of systems. In other words, the total number of formed system depends only linearly on the number density of wide binaries, which follows the background stellar density; hence, the number density of formed LMXB systems scales like the stellar number density, $n_a$ in this regime.

For densities larger than $n_{a0}$, which comprise only a small part of the galaxy, we have contributions from both the empty loss cone and the full cone regimes. If we consider the dependence on density in this regime we need to add the different components to get

$$P_{LMXB} = \int_{a_{min}}^{a_{crit}} f_a da \cdot dN \left( r \right) + \int_{a_{crit}}^{a_{max}} f_a da \cdot dN \left( r \right) = C_1 \cdot n_a \cdot \ln n_a + C_2 n_a,$$

where $C_1$ and $C_2$ are some calculable constant pre-factors. Note that the density dependence differs for different $f_a$ distributions.

To illustrate these issues, let us consider an ensemble of binaries all of which with a primary CO component with $M_{CO} = 10M_\odot$, a secondary of $0.4M_\odot$ and an age of $t = 10Gyr$, and the secondary radius of $R_e = 0.4R_\odot$ (which affects the the strength of the tidal interactions). In Fig. 1 (left panel) we show the relation between $a_{crit}$ and $n_a$ for the values described above (blue solid line). The red dashed line indicates the value of $a_{max}$, and the intersection indicates the value of $n_a$. In Fig. 1 (right panel) we see the formation probability of LMXBs for $n_a > n_{a0}$ and the two regimes are noticeable. The linear slope corresponds to eq. 17 and the decaying curve corresponds to eq. 19 (see very similar fig. in Kaib & Raymond 2014).

### 2.2.2 Calculation of the total number of LMXBs

In order to calculate the total number of field LMXBs formed in the Galactic disk, we need to integrate over the contribution from all regions of the Galaxy. Let us then consider $dN \left( r \right) = n_a \left( r \right) \cdot 2 \pi \cdot r \cdot h \cdot dr$ to be the number of stars in a region $dr$ (and scale height $h$), located at distance $r$ from the center of the galaxy. Following Kaib & Raymond (2014) and references within we model the Galactic stellar density in the Galactic disk as follows

$$n_a \left( r \right) = n_0 e^{-\left( (r-r_0) / R_t \right)}$$

where $n_0 = 0.1pc^{-3}$ is the stellar density near our sun, $R_t = 2.6kpc$ (Juric et al. 2008) is the galactic length scale and $v_0 = 8kpc$ is the distance of the sun from the galactic center. Integrating over the stellar densities throughout the galaxy we can obtain the total yield of LMXBs in the Galaxy through this process. The results of these calculations are discussed in depth in the next sections.
### Formation of LMXBs from wide binaries

In this section we estimate the number of LMXBs formed by wide binary progenitors in the Galaxy, based on the detailed calculations described in the previous sections (see section 2). The formation rates strongly depend on the frequency of the wide massive binary progenitors. Since the latter is not yet determined observationally, we consider various possible formation channels of wide-binaries containing a NS or a BH, and consider the implications of the different channels on the formation rates of LMXBs.

In subsections 3.1 and 3.1.3 we describe the formation of BH-MS and NS-MS wide binaries, respectively, through the cluster-dispersal scenario in which a single compact object captures a wide stellar companion following the dispersal of the host cluster; in subsection 3.2 we consider primordially formed wide binaries which survive the stellar evolution stage leading to the birth of the compact object. The resulting wide CO-binary populations in each of these scenarios also depend on specific assumptions regarding the formation of the compact objects and their natal kicks, if such occur. Tables 1-3 summarize the different formation channels, the various assumptions made for each specific model, and the total number of LMXBs expected to have formed through these scenarios.

#### 3 LMXB FORMATION CHANNELS

In this section we estimate the number of LMXBs formed by wide binary progenitors in the Galaxy, based on the detailed formation rates strongly depend on the frequency of the wide massive binary progenitors. Since the latter is not yet determined observationally, we consider various possible formation channels of wide-binaries containing a NS or a BH, and consider the implications of the different channels on the formation rates of LMXBs.

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#### 2.2.3 Caveats, assumptions and uncertainties

Before continuing to discuss various channels for LMXB formation through wide binaries scatterings (and the number of LMXBs they produce), we briefly mention several important caveats, uncertainties and explicit assumptions used in the suggested model.

- We tacitly assume that all tidal captures of a MS star by a CO leads to the formation of an LMXB, as similarly assumed by previous authors discussing tidal capture formation of LMXBs in dense stellar environments. However, the evolution of a tidally captured binary may not always lead to LMXB formation and other end products may also result from such evolution. For a detailed discussion of the post-capture evolution of binaries see Ray et al. (1987).

- The SMA distribution of wide binaries, and in particular high mass binaries is not well determined. In eq. 24 we use the value of $f_a$ to be log uniform, as suggested by limited observational data for low mass wide binaries, and suggested theoretical studies for the formation of wide binaries (Duchêne & Kraus 2013).

- The actual lifetime of LMXBs is not well determined; here we use a typical lifetime discussed in the literature (Verbunt 1993) of 1 Gyr.

#### 3.1 Cluster-dispersal – capture-formed wide binary progenitors

Most stars are born in stellar clusters and associations, which later disperse (Lada & Lada 2003). Following the cluster dispersal, stars may leave the cluster with small relative velocities and become bound bina-
ries (e.g. Kouwenhoven et al. 2010; Moeckel & Bate 2010; Perets & Kouwenhoven 2012). Such post-dispersal formed binaries typically have very wide orbits which could explain the origin of wide binaries in the field. In the following we consider this scenario for the origin of wide binaries and its implications for the formation of LMXBs.

### 3.1.1 BH formation with a natal kick

Consider a single BH which still resides in its host open cluster after its formation. Perets & Kouwenhoven (2012) showed that as an open cluster dissolves massive objects are more likely to capture a companion star and form wide binaries in the cluster-dispersal scenario. Primaries of mass \( m_{\text{primary}} > 5M_\odot \) have a wide binary fraction (BF) of \( f_{\text{BF}} \approx 1/2 \). A fraction of \( f_{\text{BF}} \approx 0.6 \) of these wide binaries have separations in the range \( 10^3 AU < a < 3 \cdot 10^5 AU \), and we can therefore find the number of wide binaries formed through this process. However, we still need to determine how many BHs still reside in their host clusters after their violent birth. In particular, if BHs are kicked upon formation they may escape their host cluster and will not be able to dynamically capture a wide companion.

The existence and the amplitude of BH natal kicks is still not understood (see Repetto & Nelemans 2015 for a recent overview), and we therefore consider several possible cases.

We first consider the case in which BH kicks are derived from the natal kicks of NSs that form in the process, before collapsing to become BHs. In this case we use a Maxwellian distribution for the velocities of NS natal kicks and explore three different velocity dispersions \( \sigma_{\text{NS}} = 190, 225, 270\,\text{km}\,\text{s}^{-1} \) (Fryer & Kalogera 2001; Arzoumanian et al. 2002), consistent with observations of the velocity distribution of young pulsars. We first assume that the BHs have the same momentum kick as NSs, and therefore their actual kick velocities are inversely proportional to the ratio between the mass of the BH and the mass of a typical NS, namely \( \langle m_{\text{BH}} \rangle / \langle m_{\text{NS}} \rangle \) (Fryer & Kalogera 2001). For simplicity we generally use an average BH mass of \( \langle M_{\text{BH}} \rangle = 10M_\odot \). We calculate analytically the fraction of the BH which have a velocity kick smaller than the escape velocity of the cluster \( v_{\text{esc}} \), where we consider several values for the cluster escape velocity \( v_{\text{esc}} = 1.5, 10, 20, 30, 40, 50\,\text{km}\,\text{s}^{-1} \). We can now find the number of non-escaping BHs, and thereby find the total number of wide BH-MS binaries formed from dissolving star clusters. Finally, we can use these to derive \( N_{\text{LMXB}} \), the number of LMXBs formed from such binaries

\[
N_{\text{BH-\,LMXB}} = \int P_{\text{LMXB}} \, da \cdot dN \times f_{\text{Q}} \times f_{\text{low-kick}} \times f_{\text{Single}} \times f_{\text{BF}} \times f_{\text{WF}} \times \frac{t_{\text{life}}}{t},
\]

where \( \int P_{\text{LMXB}} \, da \, dN \) is the formation rate calculation described in the previous sections, where we use typical values for the BH and MS stars: \( m_* = 0.4M_\odot \), \( M_{\text{BH}} = 10M_\odot \), \( R_* = 0.4R_\odot \) and taking \( t = 10\,\text{Gyr} \) for the overall time for wide binary scattering; \( f_0 \sim 0.001 \) is the fraction of O-star progenitors of BHs (assuming a Salpeter initial mass function) ; \( f_{\text{Single}} \sim 0.2 \) is the fraction of single stars among O-stars (binaries will be considered later on) (Duchêne & Kraus 2013). \( f_{\text{BF}} \approx 0.5 \) is the wide binary fraction as described above; \( f_{\text{WF}} \sim 0.6 \) is the wide binary fraction in the relevant separation range, as mentioned above. \( f_{\text{low-kick}} \) is the fraction of BHs formed with sufficiently low velocity kick as to be retained in the cluster before its dispersal. In order to turn the formation rates into observed numbers, one needs to account for the lifetime of the LMXB, which is assumed to be \( t_{\text{life}} \sim 10^6\,\text{yr} \). Taking these together we obtain the expected number of LMXBs in the galaxy. Fig. 2 shows the number of LMXB systems created through this channel with the parameters mentioned above. In Fig. 2 (left plot) we present the numbers for the three different velocity dispersions \( \sigma = 190, 225, 270\,\text{km}\,\text{s}^{-1} \), without accounting for the binary ionization. Fig. 2 (right plot) shows the number of LMXBs after accounting for binary ionization.

### 3.1.2 BH formation through direct collapse without a natal kick

If we assume that BH progenitors with MS mass greater than \( 30M_\odot \) form a BH through a direct collapse without a SN (Belczynski et al. 2004, 2006), the numbers of formed LMXB are significantly larger, as the host cluster retains many more BHs; effectively all of the BHs formed by stellar progenitors with \( m_{\text{progenitor}} > 30M_\odot \), irrespective of the cluster escape velocity. Note that the BH mass is not correlated with the progenitor mass in this range, and therefore this formation channels should not bias the BH masses in the formed LMXB. We find the total number of formed BH field LMXBs (with and without accounting for ionization) to be

\[
N_{\text{LMXB}} = \int P_{\text{LMXB}} \, da \cdot dN \times f_{\text{Q}} \times f_{\text{Single}} \times f_{\text{BF}} \times f_{\text{WF}} \times \frac{t_{\text{life}}}{t} \approx 3100,
\]

\[
N_{\text{ion-\,LMXB}} = \int P_{\text{LMXB-\,ion}} \, da \cdot dN \times f_{\text{Q}} \times f_{\text{Single}} \times f_{\text{BF}} \times f_{\text{WF}} \times \frac{t_{\text{life}}}{t} \approx 1100.
\]

### 3.1.3 Single NS formation via electron capture SN

The typical NS natal kicks based on the young pulsar velocity distribution (Fryer & Kalogera 2001) are much higher than the escape velocity of any stellar cluster in the Galaxy, and therefore a negligible number of NSs are expected to be retained in clusters and to capture a wide companion following the cluster dispersal. However, a subsample of NSs is known to have much lower velocity dispersion, and are thought to possibly form through an electron capture SN process (Nomoto 1984, 1987). In electron capture (EC) SN the natal kick of the newly born NS get is much lower than in the regular core collapse case. We model the natal kick values with a Maxwellian distribution with a velocity dispersion of \( \sigma_{\text{EC}} = 15\,\text{km}\,\text{s}^{-1} \). For this value of \( \sigma_{\text{EC}} \) 99% of the kicks are lower than 50\,\text{km}\,\text{s}^{-1}. In
this channel we consider every single O star in the mass range $8M_\odot < M_{\text{progenitor}} < 10M_\odot$ to become a NS through electron capture SN, and we assume the NS mass to be $\langle M_{\text{NS}} \rangle = 1.33M_\odot$ and use the same type of calculation as before to get

$$N_{\text{NS-\text{LMXB}}} = \int P_{\text{NS-\text{LMXB}}} \cdot da \cdot dN \times f_{\text{NS}} \times f_{\text{Low Kick}} \times \frac{f_{\text{Single}} \times f_{\text{BF}} \times f_{\text{WF}} \times f_{\text{Kick}}}{\tau},$$

(29)

where $f_{\text{NS}} = 7 \cdot 10^{-4}$ is the fraction of electron capture NS produced assuming a Salpeter IMF and the appropriate progenitor mass range; $f_{\text{Single}} = 0.2$ is the fraction of single O star progenitors (binaries are treated below); $f_{\text{BF}} = 0.2$ and $f_{\text{WF}} = 0.6$ are taken from Perets & Kouwenhoven (2012). In Fig. 3 we present the number of NS-LMXB systems produced via this mechanism as a function of the escape velocity of the cluster (see Table 2 and Fig. 3).

### 3.1.4 Capture formed wide triples

Previously we considered captured formed binaries. In principle non-wide binaries can also capture an additional wide orbit third companion via the same mechanism described above. This newly formed hierarchical triple system can similarly be perturbed in the field by fly-by’s. However, as the orbit of the wide companion becomes eccentric, the triple system will be driven into an unstable configuration resulting in a strong chaotic interaction typically followed by ejec-

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**Table 1.** The number of LMXB systems formed through the single BH + cluster-dispersal capture channel. The BH mass is assumed to be $\langle M_{\text{BH}} \rangle = 10M_\odot$. The upper part of the table shows the results for different natal kicks distributions (see text and Fig. 2). Results are shown for several possible type of clusters with escape velocities ranging between 1–50 km s$^{-1}$. The lower part of the table shows the results for the case where no natal kick is imparted to the BHs, for the cases where BHs with massive progenitors ($M_{\text{progenitor}} > 30M_\odot$) go through direct collapse and do not receive a natal kick. Binary ionization significantly decreases the number of available progenitors and hence the resulting number of LMXBs (compared with the cases where it is not accounted for).

| Formation Channel | Assumptions | $v_{\text{escape}}$ [km/s] | $\sigma = 190$km/s | $\sigma = 225$km/s | $\sigma = 270$km/s |
|-------------------|-------------|-----------------------------|-------------------|-------------------|-------------------|
|                   |             | $N_{\text{no ion}}$ | $N_{\text{ion}}$ | $N_{\text{no ion}}$ | $N_{\text{ion}}$ |
| Single BH + capture | momentum kick for all progenitor masses. ($m_{\text{BH}} = 10M_\odot$; $f_{\text{BF}} = 0.5$) | 1 | 0.14 | 0.05 | 0.08 | 0.03 | 0.05 | 0.017 |
|                   |             | 5 | 17.6 | 6.25 | 10.69 | 3.7787 | 6.18 | 2.2 |
|                   |             | 10 | 1.96 | 49 | 83 | 29.5 | 48.6 | 11.2 |
|                   |             | 20 | 950 | 337 | 602 | 214 | 963 | 129 |

| Formation Channel | Assumptions | $v_{\text{escape}}$ [km/s] | $N_{\text{no ion}}$ | $N_{\text{ion}}$ |
|-------------------|-------------|----------------------------|-------------------|-------------------|
| Single BH + capture | no momentum kick for $M_{\text{progenitor}} > 30M_\odot$; ($m_{\text{BH}} = 10M_\odot$; $f_{\text{BF}} = 0.5$) | don’t depend on $v_{\text{esc.}}$ | 3100 | 1100 |

Figure 2. The number of LMXB systems formed through the single BH + cluster-dispersal capture channel as a function of the cluster escape velocity. All BHs in this calculation receive momentum kicks, using Maxwellians velocity distribution for NSs, with several possible velocity dispersions, consistent with observations of young pulsars velocities. Red circles correspond to the case of $\sigma = 190$km/s$^{-1}$; blue pluses to $\sigma = 225$km/s$^{-1}$; and green X’s correspond to $\sigma = 270$km/s$^{-1}$. The BH masses are taken to be $\langle M_{\text{BH}} \rangle = 10M_\odot$. The left and right panels correspond to the LMXB numbers obtained, without and with binary ionization, respectively.

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formation of one of the three components binary. An unstable configuration occurs when the pericenter of the third companion could potentially flyby close to the CO and be tidally captured. However, the fraction of systems from the overall phase space that eventually achieve such a close approach is (following Valtonen & Karttunen 2006)

\[
f(\left| E_B \right|) d\left| E_B \right| = 3.5 |E_0|^{7/2} |E_B|^{-9/2} d|E_B|
\]

where \( E_0 \) is the total energy of the triple system, and \( E_B \) is the energy of the surviving binary that could lead to a LMXB phase. For LMXBs \( f \approx 10^{-5} \); hence the LMXB formation rate from this channel is negligible. If the third companion is captured into a highly inclined orbit with respect to the inner binary orbit, it could potentially drive the inner binary into high eccentricities through Lidov-Kozai secular evolution. This capture triggered secular evolution is beyond the scope of this study and will be discussed elsewhere. Recently, and independently, the Lidov-Kozai LMXB formation channel in triples was discussed in details by Naoz et al. (2015); earlier suggestions of LMXBs formation through secular evolution in triples have been explored by Mazeh & Shaham (1979). Another origin of LMXB in destabilized triples has been suggested by Perets & Kratter (2012).

### 3.2 Primordial binary progenitors

In the previous section we considered wide binary progenitors formed through the cluster-dispersal capture scenario. In the following we consider primordial wide binary progenitors.

#### 3.2.1 BH-MS wide binary without a natal kick

Here we consider primordial wide binaries, where again we chose typical values of \( \langle M_{BH} \rangle = 10 M_\odot \) and a \( M_{secondary} = 0.4 M_\odot \). To calculate the frequency and distribution of such binaries, we have used the BSE (Hurley et al. 2002) binary evolution population synthesis code where the initial binary population was created following the observed binary properties as reviewed by Duchêne & Kraus (2013). We find that a fraction of \( f_{BH-MS} \approx 3 \times 10^{-5} \) of the systems produce wide BH-MS binaries, assuming no natal kicks is given to the BHs. The results are summarized in Table 3. Note that fraction of formed BH-MS wide binaries when momentum kick is imparted to the BHs at birth is negligible (the escape velocity of wide binaries is very low, and the kick easily disrupts them).

### 4 DISCUSSION AND SUMMARY

In this work we explored a novel channel for formation of BH-LMXBs in the field from wide binary progenitors. We showed that a CO-MS wide binary (> 1000 AU) that undergoes perturbations from fly-by’s in the field, can have a finite probability to be kicked into an sufficiently eccentric orbit and be affected by tidal interactions. It can then evolve into a short period orbit, and eventually produce an X-ray binary once the stellar companion fills its Roche-lobe. We find that the formation rate of LMXBs through this channel strongly depends on the frequency of wide BH-MS binaries. The frequency of such binaries is sensitive to the natal kick given to BHs at birth. Silent formation of BHs from direct collapse with no natal kicks allows for the existence of a significant number of wide BH-MS binaries that can produce LMXBs. Depending on the formation scenario of the wide binaries, either as primordial binaries or through the cluster-dispersal capture scenario, we find that hundreds or thousands of BH-LMXBs could have formed in the Galactic disk through this channel, respectively, consistent with the numbers of field LMXBs inferred from observations. However, if BHs receive natal kicks at birth with comparable

| Formation Channel | Assumptions | \( v_{escape}[\text{km/s}] \) | \( N_{no\,ual} \) | \( N_{ion} \) |
|------------------|-------------|----------------|-----------|-------|
| Single NS + capture | electron capture SN for \( 8M_\odot < M_{progenitor} < 10M_\odot \); \( \sigma = 15\text{km/s} \); \( f_{33} = 0.2 \) | 1 | 1 | 0.1 |
|                  |             | 5 | 13.2 | 7.8 |
|                  |             | 10 | 95.7 | 56.5 |
|                  |             | 20 | 527 | 310 |

Table 2. The number of NS-LMXB systems formed from single electron-capture formation NS + cluster-dispersal channel as a function of the cluster escape velocity. The NS mass is taken to be \( \langle M_{NS} \rangle = 1.33M_\odot \).

Figure 3. The number of NS-LMXB systems formed from single electron-capture NS + cluster-dispersal channel as a function of the cluster escape velocity. The NS mass is taken to be \( \langle M_{NS} \rangle = 1.33M_\odot \).
momentum kick as NS natal kicks, only a few ∼ 10s – 100s LMXBs could form through this channel, depending on specific assumptions (see Table 1 for details).

NS LMXBs form in negligible numbers for typical NS natal kicks. NSs forming with low velocity natal kicks (e.g. possibly through electron-capture channel) produce up to the formation of a few tens or more LMXBs, depending on specific assumptions.

The wide-binary progenitor model for the formation of LMXBs give rise to specific observational signatures, which can differentiate them from other models. In particular they suggest a natural origin for the otherwise puzzling observed companion mass function, and the high number of field LMXBs in low density environments. These can be summarized as follows:

- **Spatial distribution**: As discussed in Sec. 2.2.1 the distribution of LMXBs in the field scales with the background stellar density like $C_1 \cdot n_\ast \cdot \ln n_\ast + C_2 n_\ast$; where typically generally the distribution of LMXBs should follow the stellar light (Gilfanov 2004; Fabbiano 2006; Paolillo et al. 2011), besides in the more dense regions in the inner parts of the Galaxy.

- **Companion mass function**: The BH-companion mass in observed LMXBs is found to be in the range 0.1 – 1 $M_\odot$, peaking at 0.6 $M_\odot$; this is inconsistent with all of the currently suggested models for LMXBs formation through common-envelope evolution (Wiktorkowicz et al. 2014). However, in our suggested wide-binary progenitor scenario the mass function of the BH companion in the LMXB is expected to follow the mass function of stellar companions in massive wide binaries. In the cluster-dispersal capture scenario origin of wide binaries, the companion mass function should generally follow the mass function of field stars. The observed mass ratio of O star binaries with wide companions scale like $q^{-2}$ (priv. comm. Maxwell Moe 2015), where $q$ is the secondary to primary mass ratio. This distribution is consistent with random pairing with present day mass function, peaking at a few 0.1 $M_\odot$. Our models therefore provides a unique signature and can explain the companion mass function in LMXBs, which challenges other formation scenarios.

- **Additional wide companions**: As mentioned here and explored in depth by Naoz et al. (2015), secular evolution in wide triples can potentially provide another alternative model for LMXB formation without a challenging common-envelope phase. One might then generally expect the existence of a wide third companion to the LMXBs. Though not excluded, such an additional companion is not required in the wide-binary progenitor model. The frequency of third wide companions to LMXBs could therefore potentially differentiate the two different models.

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### REFERENCES

Arzoumanian, Z., Chernoff, D. F., & Cordes, J. M. 2002, ApJ, 568, 289
Bahcall, J. N., Hut, P., & Tremaine, S. 1985, ApJ, 290, 15
Belczynski, K., Sadowski, A., & Rasio, F. A. 2004, ApJ, 611, 1068
Belczynski, K., Sadowski, A., Rasio, F. A., & Bulik, T. 2006, ApJ, 650, 303
Duchêne, G., & Kraus, A. 2013, ARA&A, 51, 269
Eggleton, P. P., & Verbunt, F. 1986, MNRAS, 220, 13P
Fabbiano, G. 2006, ARA&A, 44, 323
Fryer, C. L., & Kalogera, V. 2001, ApJ, 554, 548
Gilfanov, M. 2004, MNRAS, 349, 146
Hills, J. G. 1981, AJ, 86, 1750
Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, MNRAS, 329, 897
Irwin, J. A. 2005, ApJ, 631, 511
Ivanova, N., Chaichenets, S., Fregeau, J., et al. 2010, ApJ, 717, 948
Ivanova, N., Heinke, C. O., Rasio, F. A., et al. 2006, MNRAS, 372, 1043
Jurić, M., Ivezić, Ž., Broo ds, A., et al. 2008, ApJ, 673, 864
Kalb, N. A., & Raymond, S. N. 2014, ApJ, 782, 60
Kalogera, V. 1998, ApJ, 493, 368
Kalogera, V., & Webbink, R. F. 1996, ApJ, 458, 301
—. 1998, ApJ, 493, 351
Kouwenhoven, M. B. N., Goodwin, S. P., Parker, R. J., et al. 2010, MNRAS, 404, 1835
Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57
Li, X.-D. 2015, New A Rev., 64, 1
Mazeh, T., & Shaham, J. 1979, A&A, 77, 145
Moeckel, N., & Bate, M. R. 2010, MNRAS, 404, 721
Naoz, S., Fragos, T., Geller, A., Stephan, A. P., & Rasio, F. A. 2015, ArXiv e-prints, arXiv:1510.02093
Nomoto, K. 1984, ApJ, 277, 791
—. 1987, ApJ, 322, 206
Paolillo, M., Puata, T. H., Goudfrooij, P., et al. 2011, ApJ, 736, 90
Perets, H. B., & Kouwenhoven, M. B. N. 2012, ApJ, 750, 83
Perets, H. B., & Kratter, K. M. 2012, ApJ, 760, 99
Portegies Zwart, S. F., Verbunt, F., & Ergma, E. 1997, A&A, 321, 207
Ray, A., Kembhavi, A. K., & Antia, H. M. 1987, A&A, 184, 164
Repetto, S., & Nelemans, G. 2015, MNRAS, 453, 3341
Tauris, T. M., & van den Heuvel, E. P. J. 2006, Formation and evolution of compact stellar X-ray sources, ed. W. H. G. Lewin & M. van der Klis, 623–665
Valloton, M., & Karttunen, H. 2006, The Three-Body Problem, ed. Valloton, M. & Karttunen, H.
Verbunt, F. 1993, ARA&A, 31, 93
Voss, R., & Gilfanov, M. 2007, MNRAS, 380, 1685
Wiktorowicz, G., Belczynski, K., & Maccarone, T. 2014, in Binary Systems, their Evolution and Environments, 37

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