FORMATION OF BLACK HOLE LOW-MASS X-RAY BINARIES IN HIERARCHICAL TRIPLE SYSTEMS

SMDAR NAÖZ1, TASSOS FRAGOS2, AARON GELLER3, ALEXANDER P. STEPHAN1, AND FREDERIC A. RASIO1,3,4
1 Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA; snaoz@astro.ucla.edu
2 Geneva Observatory, University of Geneva, Chemin des Maillettes 51, 1290 Sauverny, Switzerland
3 Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), Northwestern University, Evanston, IL 60201, USA
4 Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA

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ABSTRACT
The formation of black hole (BH) low-mass X-ray binaries (LMXB) poses a theoretical challenge, as low-mass companions are not expected to survive the common-envelope scenario with the BH progenitor. Here we propose a formation mechanism that skips the common-envelope scenario and relies on triple-body dynamics. We study the evolution of hierarchical triples following the secular dynamical evolution up to the octupole-level of approximation, including general relativity, tidal effects, and post-main-sequence evolution such as mass loss, changes to stellar radii, and supernovae. During the dynamical evolution of the triple system the “eccentric Kozai-Lidov” mechanism can cause large eccentricity excitations in the LMXB progenitor, resulting in three main BH-LMXB formation channels. Here we define BH-LMXB candidates as systems where the inner BH-companion star crosses its Roche limit. In the “eccentric” channel (~81% of the LMXBs in our simulations) the donor star crosses its Roche limit during an extreme eccentricity excitation while still on a wide orbit. Second, we find a “giant” LMXB channel (~11%), where a system undergoes only moderate eccentricity excitations but the donor star fills its Roche-lobe after evolving toward the giant branch. Third, we identify a “classical” channel (~8%), where tidal forces and magnetic braking shrink and circularize the orbit to short periods, triggering mass-transfer. Finally, for the giant channel we predict an eccentric (~0.3–0.6) preferably inclined (~40°, ~140°) tertiary, typically on a wide enough orbit (~104 au) to potentially become unbound later in the triple evolution. While this initial study considers only one representative system and neglects BH natal kicks, we expect our scenario to apply across a broad region of parameter space for triple-star systems.

Key words: stars: kinematics and dynamics – X-rays: binaries

1. INTRODUCTION
Although there is much debate in the literature about the specific formation channel(s) for low-mass X-ray binaries (LMXBs), the “standard” scenario requires a “common-envelope” phase prior to the compact object formation to produce a tight binary (Tauris & van den Heuvel 2006). This scenario may work for LMXBs containing neutron stars. However, black hole (BH) LMXBs, which are the focus of this Letter, pose a significant challenge to this paradigm (e.g., Podsiaidowski et al. 2003). LMXBs are abundant in the local universe (e.g., Fabiano 2006), but their individual properties can only be determined in the Galactic population. To date, the accretors of 17 Galactic LMXBs have been dynamically confirmed to be BH-LMXBs (McClintock & Remillard 2006). About half (9 out of 17) of the Galactic BH-LMXBs have tight orbits (~18 hr) and low-mass (~1 M☉) main-sequence or sub-giant companions (McClintock & Remillard 2006). Mass-transfer from the lower—mass component of a binary to the more massive one leads to the expansion of the orbit, so an additional angular momentum loss mechanism is needed for the nine Galactic compact BH-LMXBs to evolve to their currently observed short periods. This mechanism is traditionally thought to be magnetic braking (e.g., Rappaport et al. 1983), which is believed to operate only in stars less massive than (~1.5 M☉), as they have a substantial outer convective zone where the dynamo effect can operate and produce the necessary magnetic fields. Hence, the initial companion mass in these systems must have been ≤1.5 M☉.

Within the standard formation channel explained above, it is unclear how a binary whose primary star is massive enough to form a BH and whose secondary is less massive than ~1.5 M☉, can survive the common-envelope phase without merging (Podsiadlowski et al. 2003). Considering the energy budget of the system (Webbink 1984), one finds that a secondary less massive than ~1.5 M☉ does not provide enough orbital energy to unbind the envelope of a BH progenitor (Podsiadlowski et al. 2003). In the last decades several ideas were put forth to address this issue that involved either potential additional sources of energy during the common-envelope phase that can help eject the envelope (e.g., Podsiaidowski et al. 2010; Ivanova & Chäuchiñez 2011; Ivanova et al. 2015) or additional angular momentum loss mechanisms that would allow companions with masses ≥1.5 M☉ to evolve to the compact BH-LMXBs that we observe today (e.g., Ivanova 2006; Justham et al. 2006; Chen & Li 2015). However, none of these alternative scenarios seem to successfully reproduce simultaneously the orbital periods, companion masses, and effective temperatures of the observed sample (Wiktorowicz et al. 2014; Li 2015).

In this letter, we propose an alternative formation channel for compact BH-LMXBs that skips the common-envelope phase all together. We show that BH-LMXBs can form due to hierarchical triple-body dynamics, in combination with General Relativity (GR), tidal forces and post-main-sequence stellar evolution. The latter includes mass loss, magnetic breaking, expansion of stellar radii and supernova (SN) dynamics. It is likely that at least some BH-LMXB progenitors originated in a triple configuration, as most massive stars reside in binaries and
higher multiples ($>70\%$ of all OBA spectral type stars (Raghavan et al. 2010; Tokovinin 2014)). From dynamical stability arguments these triple stars must be in hierarchical configurations, where the inner binary is orbited by a third body on a much wider orbit. Interestingly, a substantial number of close binaries with an accreting compact object, mainly LMXBs and their descendants (e.g., millisecond radio pulsars), are known or suspected triples (Grindlay et al. 1988; Thorsett et al. 1999; Chou & Grindlay 2001; Rasio 2001; Sigurdsson et al. 2003; Zdziarski et al. 2007; Thompson 2011; Prodan & Murray 2012, 2015). Furthermore, Ivanova et al. (2010) estimated that the most efficient formation channel for BH—white dwarf X-ray binaries in dense globular clusters may involve dynamically formed triples.

The study of these hierarchical triples can be done in the secular approximation regime (i.e., phase averaged, long-term evolution). We specifically use the “eccentric Kozai-Lidov” (EKL) mechanism (Naoz et al. 2011, 2013a). In the octupole-level of approximation, the inner orbital eccentricity can reach very high values (Ford et al. 2000; Naoz et al. 2013a; Li et al. 2014a, 2014b, 2015; Naoz & Silk 2014). When coupled with angular-momentum loss mechanisms, like tidal friction, the EKL mechanism can efficiently reduce the orbital separation of the inner binary (Naoz et al. 2011; Naoz & Fabrycky 2014), and initiate a mass-transfer phase. Thus, forming a BH-LMXB without the need for a common envelope.

The rest of this Letter is organized as follows. We begin by describing the numerical setup in Section 2; we describe the results and specifically the LMXB formation scenarios in Section 3; and finally we discuss our results in Section 4.

2. NUMERICAL SETUP

We study the secular dynamical evolution of triple stars up to the octupole-level of approximation (e.g., Naoz et al. 2013a), including tidal effects (following Hut 1980; Eggleton 1998) and GR (e.g., Naoz et al. 2013b) effects for both the inner and outer orbits. Tidal interactions operate only on the companion star to the BH and we adopt a constant viscous time of 50 years, similar to Naoz & Fabrycky (2014). Different viscous time assumptions will result in slight variations in the timescales as well as the relative contribution of each formation scenario. One of the novel additions here is that we account for the effects of stellar evolution in our calculations. This includes mass loss, the evolution of the stellar radii, and the SN of the primary star. We use the SSE (Hurley et al. 2000) stellar evolution code to evolve each individual star.

The dissipative forces due to tides on the stars are only significant if the two stars are separated by less than a few stellar radii. When the amplitude of the eccentricity oscillation during the EKL cycle is sufficiently large, the pericenter distance of the inner binary may become sufficiently small at some phase of the cycle that tidal friction drains energy from the orbit. We utilize the equilibrium tides model which dissipates energy at the pericenter. This model has proven advantageous in many different systems and studies (e.g., Naoz 2016), but it also has some drawbacks. First, it is somewhat limited in treating accurately the tidal evolution of specific objects because it is static by definition and second, it does not couple the structural or energetic changes of the star to the orbital evolution. For example, in our case, as the orbital energy is dissipated through tides in the interior of the companion star, the latter may expand responding to the extra energy source. We disregard the effect of the extra energy on the star. Thus, in that sense our estimates of orbital separation at the onset of RLO should perhaps be considered only as lower limits. Despite these caveats, we stress that the equilibrium tides model is extremely useful for qualitative description of dissipation. As our objectives are statistical in nature, this model is extremely powerful in addressing the qualitative behavior we seek to study.

All of our simulations require orbital initial conditions that satisfy dynamical stability, such that the hierarchical secular treatment is justified. The first condition is long-term stability of the triple, in which we follow the Mandling & Aarseth (2001) criterion:

$$\frac{a_2}{a_1} > 2.8 \left(1 + \frac{m_3}{m_1 + m_2}\right)^{2/5} \left(1 + e_2^2\right)^{2/5} \left(1 - 0.3 \frac{\dot{m}_{\text{BD}}}{180^2}\right).$$  \tag{1}$$

The second criterion is

$$\epsilon = \frac{e_1}{a_1\left(1 - e_2^2\right)} < 0.1,$$  \tag{2}$$

where $\epsilon$ measures the relative amplitudes of the octupole and quadrupole terms in the triple’s Hamiltonian. This is numerically similar to the stability criterion in Equation (1) (e.g., Naoz et al. 2013b).

We set $m_1 = 30.8\,M_\odot$, where the mass of the resulting BH is $7\,M_\odot$ (Özel et al. 2010; Frigos & McClintock 2015). We choose $m_2$ from a uniform distribution in the range of $0.8$–$1.5\,M_\odot$, so the final inner binary can be considered as a LMXB. A more massive tertiary will result in expanding the outer orbit due to mass loss rather quickly, reducing the strength of the EKL effects. A less massive tertiary will result in suppression of the eccentricity excitation (Teyssandier et al. 2013). Thus, we choose $m_3$ from a uniform distribution between 0.8 and 3\,$M_\odot$.

We choose the inner orbit semimajor axis, $a_1$, from a distribution that is uniform in the log between 1000\,$R_\odot$ (~4.7 au) and 1000 au. The upper limit represents the widest binaries in the Milky Way (e.g., Kaib & Raymond 2014; Antognini & Thompson 2016), while the lower limit is such as to avoid mass-transfer before the SN and allow EKL precession to be faster than GR. We choose the inner (outer) orbit eccentricity, $e_1$ ($e_2$), from a uniform distribution between 0 and 1, following Raghavan et al. (2010). Our stability requirements (see below) effectively reduce this distribution to be roughly uniform between 0.05 and 0.85 (see Figure 1).

We choose the outer orbit semimajor axis, $a_2$, from a uniform distribution in the log between $a_{2,\text{min}}$ and $a_{2,\text{max}} = 10^4$ au (e.g., Kaib & Raymond 2014). We choose $a_{2,\text{min}}$ to be the maximum value from either setting $\epsilon = 0.1$ in Equation (2), the Mandling & Aarseth (2001) criteria (Equation (1)), or requiring the quadrupole timescale to be ~6.7 Myr, which is the time at which $m_1$ will go SN. This way we guarantee that the triple configuration will not excite a large eccentricity in the inner orbit before the SN.

We should note that in this initial study we do not take into account any asymmetries in the SN explosion, as the analysis of the formation history of Galactic BH-LMXBs shows that a significant SN kick is not required for most of the systems (e.g., Willems et al. 2005; Reid et al. 2014), with robust evidence for a natal kick imparted onto a BH coming only from one system (Gualandris et al. 2005; Frigos et al. 2009). More recently, Repetto et al. (2012) and Repetto & Nelemans (2015), using
the positions of BH-LMXBs in the Galactic potential as observational constraints, concluded that BHs likely receive natal kicks similar in magnitude to neutron stars. However, observational constraints, concluded that BHs likely receive.

Figure 1. Orbital consequences of supernova. Initial (the green dashed lines) and post-SN stable (the gray solid lines) distributions of orbital properties (orbital separation and eccentricity) of the inner and outer binary as well as strength of the octupole approximation. About 35% from the initial condition end up in a post-SN stable hierarchical configuration.

In Figure 1 we show the results of the SN on the different orbital parameters (specifically on $a_1$, $e_1$, $e_2$, and $e$). The SN tends to widen the orbit and thus reduce the strength of the octupole-level of approximation effects. Furthermore, the eccentric orbits are more likely to be disrupted by the SN or become unstable.

3. LMXB CANDIDATE FORMATION SCENARIOS

During the EKL evolution the inner orbit eccentricity is excited, which can result in crossing of the Roche limit. Following Eggleton (1983) we define the dimensionless number:

$$
\mu_{\text{Roche}} = \frac{(m_1/m_2)^{2/3}}{0.6(m_1/m_2)^{2/3} + \ln(1 + (m_1/m_2)^{1/3})}.
$$

The Roche limit is then defined by

$$
d_{\text{Roche}} = \frac{R_1}{\mu_{\text{Roche}}},
$$

where $R_1$ is the radius of the star. In our simulations if the BH-companion star pericenter distance $d_1(1 - e_1)$ becomes smaller than $d_{\text{Roche}}$, we assume that the star will overflow its Roche-lobe. We stop the calculation here and identify this system as a LMXB candidate.

We denote the parameters of systems that cross their Roche limit with the subscript “RLO” (Roche-Lobe Overflow). In total, we follow the evolution of 2601 post-SN hierarchical triple systems for 10 Gyr, covering the initial parameter space described in Section 2. We find a little more than 5% of our runs to be LMXB candidates. Of these, we identify three formation channels and show an example evolutionary sequence for each one of them in Figure 2. Figure 3 shows the distribution of orbital properties of our population of LMXB candidates for the inner orbit at the onset of RLO. The three formation channels of our LMXB candidates can be easily distinguished in the upper left panel of Figure 3. The three channels are:

1. **Eccentric.** The majority (~81%) of our LMXB candidates cross their Roche limit when their inner orbit reaches an extremely high eccentricity ($e_{i, \text{RLO}} \gtrsim 0.999$). This takes place on a shorter timescale than the typical extra precession timescale (such as tides, rotational bulge, and the GR precession timescales), and the orbit becomes almost radial. A typical timescale to get to RLO is $\sim 10^{7}$–8 year, while both $m_2$ and $m_3$ are on the main sequence (see Figure 2, left panel, and Figure 3). We note that numerically resolving the maximum eccentricity requires very small time steps. Furthermore, due to the chaotic nature of the system and the limitation of the double averaging method (e.g., Antonini & Perets 2012; Katz & Dong 2012; Antognini et al. 2014; Antonini et al. 2014; Bode & Wegg 2014), we probably underestimate the maximum eccentricity reached in many of these high peaks. Hence, the overall number of systems that reach RLO may be higher, and the true distribution of RLO times may be shifted to slightly shorter values than depicted in Figure 3. We note that about ~30% of the systems reach such high eccentricities to significantly

\footnote{Note that in this simplified analysis we do not distinguish between tidal disruption and RLO.}

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**Figure 1.** Orbital consequences of supernova. Initial (the green dashed lines) and post-SN stable (the gray solid lines) distributions of orbital properties (orbital separation and eccentricity) of the inner and outer binary as well as strength of the octupole approximation. About 35% from the initial condition end up in a post-SN stable hierarchical configuration.
violate the double averaging procedure (order of magnitude violation of Equation\(18\)) in Antonini et al.\(2014\). This may cause even larger eccentricities, which can lead to a head-on collision between the star and the BH.

2. Giants. In the second class of systems (\(\sim 11\%\)) the inner orbit does not reach the same extreme eccentricities for the inner binary to reach RLO. The inner BH-companion star eventually evolves to become a giant star; it is at that point that it fills its Roche-lobe, generally still at a highly eccentric orbit (\(e_1 \sim 0.9\)). As shown in the example depicted in the middle panels of Figure 2, after the outer star lost its mass, the eccentricity oscillations slowed down (labeled “Slower EKL” in the figure) but still continued to be excited to somewhat large values. In the first stellar expansion episode, tides shrunk the inner orbit’s semimajor axis, which then expanded again due to mass loss in the red giant and AGB phase. In the second

Figure 2. Example evolutionary sequences corresponding to the three formation scenarios. We consider (from top to bottom) the inclination \(i_1\), the eccentricity of the inner (red) and outer (cyan) orbits, shown as \(1 - e\), the semimajor axis of the inner (red) and outer (cyan) orbits, as well as the pericenter distance of the inner orbit (the gray line). Also shown is \(a_{\text{Roche}}\), as defined in Equation\((4)\). The last two bottom rows show the BH inner companion star’s radius, \(R_1\), and mass, \(m_1\), as well as the tertiary companion’s mass \(m_3\). Left panels show the time evolution of a system starting right after the BH formation (i.e., post-SN) with \(m_1 = 1.06 M_\odot\), \(m_2 = 1.91 M_\odot\), \(a_1 = 590\) au, \(a_2 = 6025\) au, \(e_1 = 0.64\), \(e_2 = 0.52\), \(i = 105.5^\circ\), and the argument of pericenter of the inner and outer orbits are set to 148.8° and 332.7°, respectively. The post-SN properties of the system shown in the middle panels are \(m_1 = 1.24 M_\odot\), \(m_2 = 2.55 M_\odot\), \(a_1 = 58.3\) au, \(a_2 = 1161.1\) au, \(e_1 = 0.64\), \(e_2 = 0.36\), and \(i = 110.6^\circ\), with the \(a_1\) and 132.8°, respectively. Finally, in the right panel’s argument of pericenter of the inner and outer orbits set to 338.8° the post-SN properties are \(m_1 = 0.905 M_\odot\), \(m_2 = 1.47 M_\odot\), \(a_1 = 580.2\) au, \(a_2 = 4114.2\) au, \(e_1 = 0.59\), \(e_2 = 0.15\), and \(i = 140.7^\circ\), with the argument of pericenter of the inner and outer orbits set to 292.4° and 186.8°, respectively. For illustration purposes we allowed the system to evolve beyond the RLO point.
As expected from the EKL mechanism, in our models the LMXB candidates form preferentially in systems with initial inclinations between the inner and the outer orbit close to 90°, and with a larger range of mutual inclination, for stronger octupole contribution (see the bottom right panel in Figure 4). The middle right panel in Figure 4 shows that modeled LMXB candidates are more likely to be found in triple systems with eccentric outer orbits, which translates to larger octupole strengths (Equation 2)). Note that the initial mutual inclination is not conserved (as depicted in the bottom left panel in Figure 4), similarly to Naoz & Fabrycky (2014).

Finally, BH–white dwarf binaries that survive to the end of 10 Gyr of evolution without RLOF are typically on wide orbits (denoted as “No RLO” in Figure 4 and with a minimum separation of 8.9 au; see top left panel). Their white-dwarf tertiarities are also on a wide orbits (the top right panel in Figure 4) and most likely will become unbound due to galactic tides (Kai & Raymond 2014) or collide with single stars in the field (Antognini & Thompson 2016) after approximately a Hubble time.

4. DISCUSSION AND CONCLUSIONS

We study the formation of BH-LMXBs through secular three-body interactions. We consider the octupole-level of approximation of the hierarchical three-body problem, including GR, tidal effects and post main-sequence stellar evolution, which includes mass loss, inflation of stellar radii, and SN for the BH progenitor. We run a large Monte-Carlo sample of simulations (2601), of which about 5% overflow their Roche-lobe and become LMXB candidates. We identify three distinct formation channels for LMXB candidates, which we label as “eccentric,” “giant,” and “classical.”

The “eccentric” channel describes systems for which their eccentricity is excited to extremely large values (at RLO $e_1 \gtrsim 0.999$), their orbit becomes almost radial, and they fill their Roche-lobe. This scenario represents the majority of our simulated systems ($\sim 81\%$). Due to the large eccentricity and the wide inner orbit, the fate of these systems after the onset of RLO is somewhat uncertain. We speculate that ejecta from non-conservative mass-transfer during periastron RLO will form a circumbinary disk which may in turn help, through tidal interaction, to quickly circularize the inner orbit.

The “giants” formation channel represents a unique combination of EKL and stellar evolution ($\sim 11\%$ from all LMXBs). Since the remaining life of the evolved donor star is short, the lifetime of the X-ray bright phase is expected to be short ($\sim$ few Myr), and hence the contribution of this scenario to the observed BH-LMXB population is probably limited.

Both the “eccentric” and “giants” formation scenarios take place during high eccentricity peaks. Sepinsky et al. (2007, 2009) studied the effect of RLO mass-transfer in eccentric binary orbits, assuming a $10^{-9} M_\odot$ yr$^{-1}$ mass-transfer
rate at periastron. They found that for the mass ratios we consider here, the circularization timescale on the order of 1–10 Gyr. However, their analysis does not include the forced eccentricity oscillations due to a third body or post-main-sequence donors, which we expect will affect the overall dynamics of such systems.

Systems that follow the “classical” scenario (∼8% of LMXB candidates in our simulations) form compact LMXBs, with properties similar to the observed ones of Galactic compact BH-LMXBs (McCintock & Remillard 2006) and similar to the theoretically estimated properties at the onset of RLO (e.g., Fragos et al. 2009; Fragos & McClintock 2015; Repetto & Nelemans 2015). The tertiary companion of such a BH-LMXB is expected to be a white dwarf at a large orbital separation on the order of several thousand au, which renders them effectively undetectable. The lifetimes of these systems in the LMXB phase are expected to be on the order of a Gyr; however, their formation timescale is 10^9 years (as deduced from the colors in Figure 3) in contrast to ∼Gyr formation timescales predicted by the standard formation channel from primordial binaries (Fragos et al. 2013). The “classical” formation channel is the least efficient one in our Monte-Carlo simulations; however, its efficiency is strongly dependent on the assumed strength of the tidal forces, and hence it is difficult to accurately estimate its relative contribution.

Finally, we estimate the current number of BH-LMXB that may exist in a galaxy such as the Milky Way as

$$N \sim \frac{\Delta N}{\Delta t} \tau_{\text{BH-LMXB}} \sim 280 \times \left( \frac{f_{\text{stable}}}{0.35} \right) \times \left( \frac{\text{SFR}}{1 M_\odot \text{yr}^{-1}} \right) \left( \frac{f_{\text{IMF}}}{0.0018 M_\odot} \right) \left( \frac{f_{\alpha}}{0.5} \right) \left( \frac{f_{m/m_1}}{0.05} \right) \left( \frac{f_{\text{KEL}}}{0.0175} \right)$$

for all formation channels combined (note that multiplying the relevant fractions gives $\Delta N/\Delta t \sim 2.8 \times 10^{-7}$ yr^{-1}). The latter number becomes ∼65 if we consider only the “classical” scenario. In the above Equation, we assumed that 100% of all massive stars are in triples, and the inner binaries initially have a flat mass ratio distribution (Sana et al. 2012). The fraction of stars with a mass above 30 $M_\odot$ is drawn from a Kroupa (2001) IMF ($f_{\text{IMF}}$). $f_\alpha$ is the fraction of systems with the inner binary separation assumed in our initial conditions and $f_{m/m_1}$ is the fraction of systems with the mass ratio used in our simulations. Finally, $f_{\text{KEL}}$ is the efficiency of the EKL mechanism, estimated for all channels to be $0.35 \times 0.05 = 0.0175$, while for the classical scenario it is $0.0175 \times 0.03 = 0.0014$. We also take into account only the 35% of systems that remained stable after the supernova ($f_{\text{stable}}$). The assumption here is that the lifetime of all BH-LMXBs is $\tau_{\text{BH-LMXB}} \sim 1$ Gyr; however, this may not be the case for all channels. A proper comparison with the observed population should take into account the transient behavior of LMXBs as well as the selection effects.

In this paper we presented a proof of concept that BH-LMXBs can be formed naturally via three-body gravitational dynamics. Here, we neglected the SN kicks possibly imparted to BHs and we considered only one representative values for the BH mass ($7 M_\odot$). A follow-up study will explore the full parameter space of relevant triple configurations, necessary to better quantify the overall BH-LMXB formation rate through this channel. While significant BH birth kicks could disrupt some fraction of triple systems, we do not think that this could dramatically reduce the BH-LMXB formation rate. For example, a system with $a_1 = 6.5$ au, $e_1 = 0.3$, $a_2 = 380$ au, and $e_2 = 0.7$ and an argument of periapsis set initially with zero ($90^\circ$) for the outer (inner) orbit, would easily survive the SN with a kick magnitude up to 30 km s^{-1}. Systems with more massive BHs (say ∼10–20 $M_\odot$), which are not considered here, would survive even more easily. Thus, our results show that hierarchical triple systems provide a promising environment for the formation of BH-LMXBs.

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