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Widening of Binaries via Non-conservative Mass Transfer as a Formation Channel for Gaia Black Hole Systems

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ABSTRACT

The detected Gaia systems hosting compact objects challenge standard models of binary star evolution. In particular, if the observed black hole (BH) systems evolved in isolation, it is expected that they underwent a mass transfer phase. Given their highly unequal mass ratios, such mass transfer is dynamically unstable within standard models, leading to either a stellar merger or a final binary with a very short orbital period. In contrast, the observed systems have much wider orbits than predicted, making their formation within conventional evolutionary frameworks difficult to reconcile. With the aid of detailed binary evolution calculations, we test whether fully non-conservative mass transfer, where mass is lost from the system carrying the specific angular momentum of the donor's center of mass, can explain the properties of two of Gaia BH systems. This mass-loss geometry differs from the standard isotropic re-emission model, which assumes mass loss from the accretor's vicinity. We find that our mass-loss model, without the need for fine-tuning, reproduces the observed orbital periods of the two Gaia BH systems remarkably well across a wide range of initial conditions. This scenario, therefore, offers a plausible formation pathway for these systems. We speculate that orbital widening during mass loss could result from the unequal Roche-lobe sizes of the components and eruptive mass loss driven by the donor's high-opacity subsurface layers. Similar mass-loss may also be relevant for all other classes of post-mass-transfer binaries that face analogous evolutionary challenges, including Gaia neutron star and white dwarf systems, binaries hosting stripped-envelope Wolf–Rayet stars, and low-mass X-ray binaries.

Keywords: Black hole physics — Binary stars — Stellar evolution — Stellar mass loss — Gaia mission

1. INTRODUCTION

The European Space Agency's Gaia mission (Gaia Collaboration et al. 2016, 2018; L. Lindegren et al. 2021) has revolutionized our view of the stellar populations in the Milky Way. One of the more significant results was the identification of candidates for binary systems harboring non-accreting black holes (BHs), inferred through the orbital motion of luminous stellar companions (K. El-Badry et al. 2023a,b; S. Chakrabarti et al. 2023). All so far reported BH systems: Gaia BH1, Gaia BH2, and Gaia BH3 comprise of a low mass star in a relatively wide orbit around an unseen companion with a dynamically inferred mass consistent with stellar-mass BHs. These discoveries provide a new and valuable window into the demographics of BHs, complementary to those probed by spectroscopic surveys, X-ray binaries and gravitational-wave events.

The Milky Way is expected to host over a hundred thousand stellar-origin BHs, although the vast majority are expected to be single (S. L. Shapiro & S. A. Teukolsky 1983; E. P. J. van den Heuvel 1992; A. Olejak et al. 2020). The number of BHs remaining in binaries is significantly lower, possibly amounting to up to 10% of the

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total population (A. Lamberts et al. 2018; M. Renzo et al. 2019; G. Wiktorowicz et al. 2019; A. Olejak et al. 2020; A. Vigna-Gómez & E. Ramirez-Ruiz 2023). However, this fraction depends sensitively on several uncertain factors such as the initial binary and multiple fractions, contribution of stellar mergers (and mass transfer physics), and systems' disruption at BH formation. Among the surviving binaries, most are expected to be wide, non-interacting systems containing a BH and either another compact object or a low-mass, long-living star as the companion (G. Wiktorowicz et al. 2019; K. Breivik et al. 2017, 2019; A. Olejak et al. 2020). From this perspective, the discovered Gaia BH systems with low mass stellar companions were expected.

The real challenge emerges when considering the orbital periods of these systems: ~ 186 and 1277 days (P. Nagarajan et al. 2025). If they formed in isolation, such separations would almost certainly require a previous phase of mass transfer within the framework of classical binary evolution models (although see A. Gilkis & T. Mazeh 2024 and M. U. Kruckow et al. 2024, discussed below). Given their highly unequal mass ratios, such mass transfer is expected to be dynamically unstable (e.g., H. Ge et al. 2015; K. Pavlovskii et al. 2017; H. Ge et al. 2020b,a), leading to either a stellar merger or a very tight post-common envelope (CE) binary (B. Paczynski 1976; N. Ivanova et al. 2013). Therefore, the observed relatively wide orbits are inconsistent with predictions from standard binary evolution, making their formation challenging to explain. Interestingly, a similar problem has also been reported for other types of post-mass-transfer binaries, for example, the systems detected by Gaia hosting white dwarfs (N. Yamaguchi et al. 2025) or neutron stars (K. El-Badry et al. 2024; D. Chattopadhyay et al. 2025).

Several formation channels and stellar evolutionary models have been proposed to explain the properties of Gaia BH systems. In the case of Gaia BH3, its association with the metal-poor ED-2 stream in the Galactic halo suggests that it may have been ejected from a disrupted globular cluster, suggesting a dynamical formation scenario (D. Marín Pina et al. 2024; E. Balbinot et al. 2024). Gaia BH3, owing to its longer orbital period and low metallicity, may have also entirely avoided mass transfer under the isolated binary formation scenario (G. Iorio et al. 2024; K. El-Badry 2024). In contrast, the present-day orbital separations of Gaia BH1 and Gaia BH2 appear too small to completely avoid binary interactions once the BH progenitor leaves the main sequence, at least within the framework of classical population synthesis models (I. Kotko et al. 2024; P. Nagarajan et al. 2025). We therefore focus in this work on the Gaia BH1 and Gaia BH2 systems.

Some alternative explanations based on detailed binary evolution calculations suggest that the progenitors of Gaia BH1 and Gaia BH2 could have avoided a mass-transfer phase if different calibrations of stellar evolution parameters are adopted. One possibility is that convective overshooting above the core and into the radiative envelope limits the radial expansion of massive stars, yielding substantially smaller maximum radii for supergiant progenitors (A. Gilkis & T. Mazeh 2024). Such stars could have remained within their current orbital separations without triggering Roche-lobe overflow (RLOF). Another proposed explanation involves enhanced stellar wind mass loss at high metallicity, which can simultaneously reduce the stellar radius and widen the orbit, thereby preventing binary interaction (M. U. Kruckow et al. 2024). Finally, these systems might also have a dynamical origin. For instance, hierarchical triple evolution could reproduce the present-day configuration if an inner binary merger occurred (Z. Li et al. 2024).

In this work, we investigate whether the observed properties of Gaia BH1 and Gaia BH2 can be reproduced through fully non-conservative mass transfer within the framework of isolated binary evolution. In contrast to the commonly adopted isotropic re-emission model, where mass is lost from the vicinity of the accretor, we propose an alternative scenario in which all transferred material is lost from the system carrying the specific angular momentum of the donor's center of mass. Under this assumption, the orbit expands during the mass-transfer phase rather than shrinking excessively, allowing the interaction to remain stable even for systems with highly unequal mass ratios. We argue that such a mass-loss geometry and the resulting orbital widening are physically plausible, given the strongly unequal Roche-lobe sizes of the components and the high-opacity subsurface layers of the donor, which would enhance wind-like mass loss.

Table 1. The parameters of Gaia BH1 and BH2: (from top to bottom) the orbital period P in days, the eccentricity, BH mass $M_{\rm BH}$ and companion star mass $M_\star$ [$M_\odot$] in solar units adopted from K. El-Badry et al. (2023a); S. Chakrabarti et al. (2023); K. El-Badry et al. (2023b).

Parameter	Gaia BH1	Gaia BH2
P [d]	185.52 ± 0.08	1276.7 ± 0.6
e	$0.439^{+0.004}_{-0.003}$	0.5176 ± 0.0009
$M_{\rm BH}$ [$M_\odot$]	$9.32^{+0.22}_{-0.21}$	8.94 ± 0.34
$M_\star$ [$M_\odot$]	0.93 ± 0.05	1.07 ± 0.19

2. METHOD

We use the stellar evolution code MESA (version r23.05.1; B. Paxton et al. 2011, 2013, 2015, 2018, 2019; A. S. Jermyn et al. 2023) to study the binary evolution of the progenitors of the Gaia BH1 and Gaia BH2 systems, with their parameters presented in Table 1. We adopt a metallicity of $Z = 0.01$, which is in good agreement with both observed systems (K. El-Badry et al. 2023a,b). The overshooting parameters for the donor star have been calibrated to match observational constraints for massive stars (I. Brott et al. 2011). We evolve both stars from the zero-age main sequence, including tidal interactions following P. Hut (1980). We assume that each stellar layer is synchronized independently, the donor has a radiative envelope, the accretor has a convective envelope, and standard tidal efficiency factors are set to unity.

We adopt the "Kolb" mass transfer scheme (U. Kolb & H. Ritter 1990). Motivated by low companion masses, we assume fully non-conservative mass transfer. In our default model, all mass lost during the RLOF carries away the specific angular momentum of the donor's center of mass (α=1, β=δ=γ=0, see notation in G. E. Soberman et al. 1997). The angular momentum loss associated with mass lost $\dot{J}_{\rm ml}$ from the vicinity of the donor is expressed by the formula:

$$\dot{J}_{\rm ml} = \dot{M}\ \left(a\, M_{\rm acc}/(M_{\rm acc} + M_{\rm don})\right)^2\ (2\pi/P)$$

where $\dot{M}$ is the mass loss rate from the donor. Here, $M_{\rm acc}$ and $M_{\rm don}$ denote the masses of the accretor and the donor, a is the orbital separation, P is the orbital period. The factor $a\, M_{\rm acc}/(M_{\rm acc} + M_{\rm don})$ corresponds to the distance from the system's center of mass to the center of mass of the donor star.

This assumption corresponds to a spherically symmetric Jeans-mode mass loss carrying the specific angular momentum of the donor's center of mass (e.g., S.-S. Huang 1963; G. E. Soberman et al. 1997; T. M. Tauris & E. P. J. van den Heuvel 2006). In practice, this represents a spherically symmetric outflow from the surface of a non-rotating donor. Such an assumption is standard when stars lose mass through stellar winds, but it has also occasionally been applied to systems undergoing RLOF (J. R. Hurley et al. 2002). Under this prescription, the associated angular momentum loss is relatively modest for the considered mass ratio ($M_{\rm don} \gg M_{\rm acc}$), and the orbit generally tends to expand in response to mass loss, similar to the case of isotropic stellar winds.

By contrast, if mass is lost from the vicinity of the accretor or through the outer Lagrangian points (L2 or L3), in the evaluated mass ratio regime the escaping material carries away substantially larger specific orbital angular momentum (e.g., T. M. Tauris & E. P. J. van den Heuvel 2006), leading to rapid orbital shrinkage rather than expansion.

3. BINARY EVOLUTION

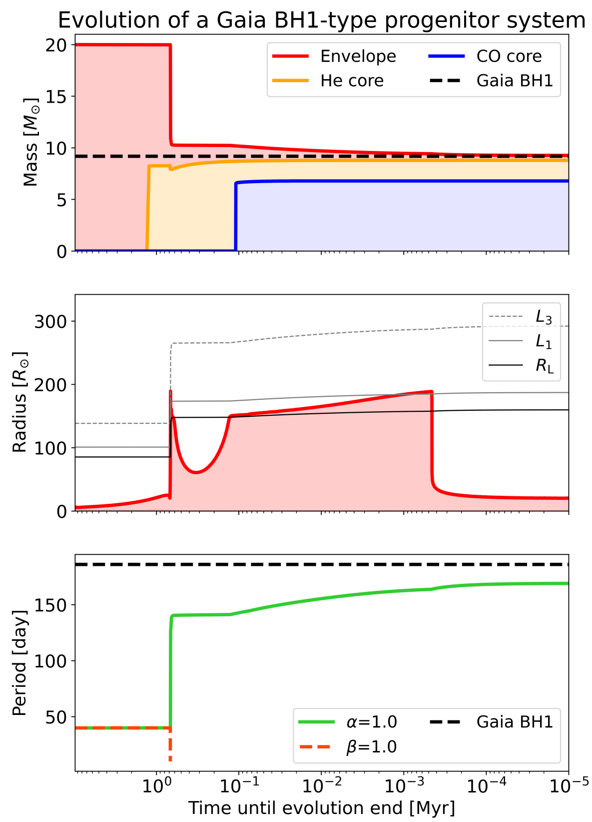

Figure 1. Evolution of the Gaia BH1 progenitor system. The top panel shows the evolution of the donor's mass, with the red, yellow, and blue curves representing the hydrogen-rich envelope, helium core, and carbon–oxygen core, respectively. The middle panel presents the evolution of the donor's radius, along with the Roche lobe radius $R_{\rm L}$ and the sizes corresponding to the inner Lagrange point L1 $\approx a\,(1 - (M_{\rm acc}/(3M_{\rm don}))^{1/3})$ and outer Lagrange point L3 $\approx a(1 + 5/12\,(M_{\rm acc}/M_{\rm don}))$ located behind the donor (see Fig. 2). The bottom panel shows the evolution of the orbital period. The green line corresponds to the model assuming mass loss carrying the specific angular momentum of the donor's center of mass (orbital widening), while the orange dashed line represents the standard assumption of isotropic re-emission from the accretor (rapid orbital shrinkage). The black dashed line marks the observed properties of the Gaia BH1 system. The timescale is expressed as the logarithm of the remaining time until the end of evolution, defined as the point of central helium depletion.

Figure 1 presents an example of an evolutionary track leading to a system with properties similar to Gaia BH1. The initial binary system consists of a $20\,M_\odot$ BH progenitor and a $1\,M_\odot$ companion on a circular orbit with a period of 40 days, corresponding to a separation of $\sim 150\,R_\odot$. Note that the low mass companion could still be on its pre-main sequence track at the moment of primary (the more massive star) zero-age-main sequence (R. Kippenhahn et al. 2013; I. Baraffe et al. 2015). After approximately 9 Myr, the primary evolves off its main sequence and undergoes significant radial expansion, triggering a rapid mass transfer episode lasting ~ 0.1 Myr with a peak rate of $3.3 \times 10^{-3}\,M_\odot\,\mathrm{yr}^{-1}$.However, as shown in the middle panel of Figure 1, the inner Lagrange point L1 is only slightly overfilled. The outer Lagrange point L3, situated behind the donor, remains unfilled, as expected from the system geometry characteristic of the considered mass ratios (S. H. Lubow & F. H. Shu 1975; P. P. Eggleton 1983; T. Ryu et al. 2025).

Due to mass loss, the system's orbital period increases from 40 to 140 days. The donor rapidly loses almost $10\,M_\odot$, removing most of its hydrogen-rich envelope. Following this, the donor's radius contracts and for over ~ 0.4 Myr (most of the remaining core-He burning) the star detaches from its Roche-lobe, halting mass transfer. During this stage, the (partially) stripped donor may already appear as a WR star (see Discussion 5). At final stages of He burning, the star expands once more, initiating a second mass transfer phase lasting $\sim$ 0.2 Myr. This phase proceeds at a significantly lower rate than during the former phase, at $\sim 10^{-5}$–$10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$, and results in the loss of an additional $\sim 1\,M_\odot$. Ultimately, the mass transfer ceases, leaving behind a $\sim 9\,M_\odot$ stripped helium core and a low-mass companion in a widened orbit with a period of around 174 days. Subsequently, the stripped star may undergo core collapse to a BH, accompanied by low, asymmetric mass loss, for example through neutrino stream emission (C. L. Fryer 1999). This can lead to a modest orbital widening and induce an eccentricity in the binary system; see broader discussion on the possible origin of eccentricity in Section B of the Appendix.

The evolutionary pathway obtained for the Gaia BH2 system is qualitatively very similar to the scenario presented for Gaia BH1, differing primarily in its wider initial orbital separation. A detailed, analogous description of the Gaia BH2 progenitor system is provided in Appendix A.

4. PHYSICAL MOTIVATION FOR THE MODEL

There are several reasons to expect enhanced mass loss from the vicinity of the donor in relatively wide, highly unequal-mass systems with a massive donor, such as those studied in this work. Below, we outline some factors that together could lead to the assumed mass-loss geometry, thereby limiting angular momentum loss and preventing unstable mass transfer in the progenitors of the Gaia BH systems.

First, given the extreme mass ratios in these systems, it is plausible that most of the mass transfer stream launched near L1 is not confined to the accretor's Roche lobe due to its small size. Figure 2 illustrates the geometry of binaries at the onset of RLOF for three different mass ratios, all with the same orbital separation and total component mass. The left panel shows a system with a donor-to-accretor mass ratio of $M_\mathrm{don}/M_\mathrm{acc} = 20$, as in the progenitors of Gaia BH1 and BH2. In such an extreme-mass-ratio binary, the accretor's Roche lobe is very small relative to the donor's surface, which can strongly influence mass-loss behavior, especially at high mass transfer rates. We speculate that during the initial phase of mass transfer, some material may flow through L1, but once the accretor's Roche lobe is filled, this channel can be blocked.

In the scenario considered here, mass must be lost with the specific angular momentum of the donor's center of mass to avoid instability. Outflows through the Lagrange point L3 behind the donor would remove substantially more angular momentum and drive orbital contraction; however, for the mass ratios relevant here, where the donor is far more massive than the accretor, L3 overflow is unlikely (S. H. Lubow & F. H. Shu 1975; P. P. Eggleton 1983; T. Ryu et al. 2025). The considered systems with $M_\mathrm{acc} \ll M_\mathrm{don}$, low initial stream velocities and asynchronous donor rotation further modify the geometry of the mass-loss stream, potentially leading to substantial donor self-accretion (P. J. Davis et al. 2013, 2014; D. D. Hendriks & R. G. Izzard 2023). Such effects are not captured in the idealized treatments of mass-transfer streams commonly used in binary evolution codes, yet they may play a important role in determining both the orbital and mass evolution of the systems.

The ideal scenario for the angular momentum budget assumed in our models would be if the majority of the mass was lost from the donor in the form of an enhanced wind. Massive stars, particularly at moderate to high metallicities, develop high-opacity subsurface layers in which the local luminosity can exceed the Eddington limit (P. C. Joss et al. 1973; Y.-F. Jiang et al. 2015; D. Sanyal et al. 2015, 2017; A. S. Jermyn et al. 2023). Such locally super-Eddington conditions may unbind the overlying material and drive strong, eruptive mass loss at rates of up to $\sim 10^{-2}\,M_\odot\,\mathrm{yr}^{-1}$(S. P. Owocki 2015; E.

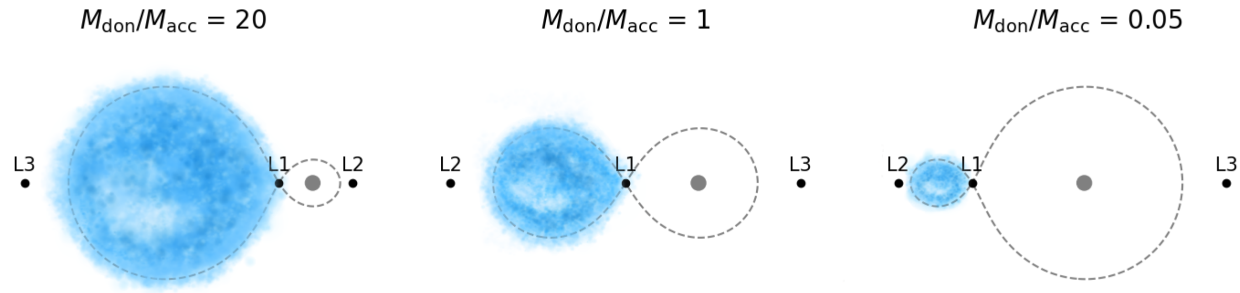

Figure 2. Illustration of the geometry of systems at the onset of RLOF for three different mass ratios, all with the same orbital separation and total components mass. The left panel shows a system with a donor-to-accretor mass ratio $M_{\rm don}/M_{\rm ac} = 20$, as in case of Gaia BH1 and BH2 progenitors. For comparison, cases with equal-mass components ($M_{\rm don}/M_{\rm ac} = 1$) and with the opposite extreme mass ratio ($M_{\rm don}/M_{\rm ac}$ =0.05) are also presented.

Quataert et al. 2016; S. J. Cheng et al. 2024), potentially explaining the observed paucity of red supergiants above $\gtrsim 30\,M_\odot$. Interestingly, similar opacity peaks appear in the stellar structure profiles of the Gaia BH1 and BH2 progenitors, suggesting that analogous processes could have contributed to their formation. The amount of mass in sub-surface super-Eddington layers depends on the effective temperature of the star (S. J. Cheng et al. 2024) and is the largest for cool donors in wide orbits. Figure 3 shows the opacity profiles of the donor stars at the onset of RLOF, based on our `MESA` models, plotted as a function of both mass and radius. For comparison, the Eddington opacities for the modeled stars are approximately 1.66 $\rm cm^2\,g^{-1}$ for Gaia BH1 and 1.53 $\rm cm^2\,g^{-1}$ for Gaia BH2. The helium- and iron-enriched opacity peaks exceed the Eddington limit, implying that these layers are formally unbound even for a non-rotating single star due to strong radiative pressure. The corresponding Eddington thresholds would be even lower for more massive or rotating donors, as centrifugal support reduces the effective gravity.

There are several reasons why being in a binary system can facilitate stronger winds from the donor star. In our models, parts of the stellar envelope extend beyond the Roche-lobe radius, further weakening the gravitational binding. The opacity peaks shown in Fig. 3 give rise to subsurface convective zones (M. Cantiello et al. 2009), in which tidal dissipation is expected to be much stronger than in the rest of the radiative envelope (J. P. Zahn 1977; G. I. Ogilvie 2014). This could lead to these layers becoming tidally synchronized with the orbit, thereby further reducing their effective gravity. Moreover, self-accretion may cause additional accumulation of material above the Roche-lobe boundary, enhancing mass loss from the outer layers. Embedding such a star in a binary system naturally facilitates further mass loss, particularly in wide systems with large mass ratios. Note that our donors—especially if initially more massive than selected examples—could be example of Luminous Blue Variables (LBVs). In fact, several LBVs are found in wide binary systems with eccentric orbits, and their enhanced mass loss is expected to be driven by various forms of binary interactions, depending on the particular system (see, e.g., N. Smith 2026 and references therein).

If the system were initially eccentric, it could retain part of this eccentricity throughout the mass-transfer phase, as suggested by observations of wide binaries (G.-M. Oomen et al. 2018, 2020; A. Escorza et al. 2020; J. Müller-Horn et al. 2025). The evolution of systems undergoing eccentric mass transfer remains poorly understood, but recent theoretical modelling (K. A. Rocha et al. 2025; A. Parkosidis et al. 2025) indicates that it may result in more orbital widening than predicted for circular systems. In the mass-ratio regime of our systems, stable mass transfer nevertheless requires substantially lower angular momentum loss—such as specific angular momentum of the donor's center of mass—compared to standard binary evolution prescriptions (i.e., isotropic re-emission).

It is worth noting that some binary evolution codes have historically allowed for mass-loss geometries in which the lost material carries away the specific angular momentum of the donor's center of mass during Roche-lobe overflow. For example, this treatment was adopted as the default in the original prescriptions of J. R. Hurley et al. (2002).

5. DISCUSSION

In this Letter, we present a new evolutionary model that, with minimal assumptions and little fine-tuning, reproduces the formation of the Gaia BH1 and BH2 systems remarkably well. Our scenario assumes fully non-conservative mass transfer, with all transferred material lost from the system while carrying the specific angu-

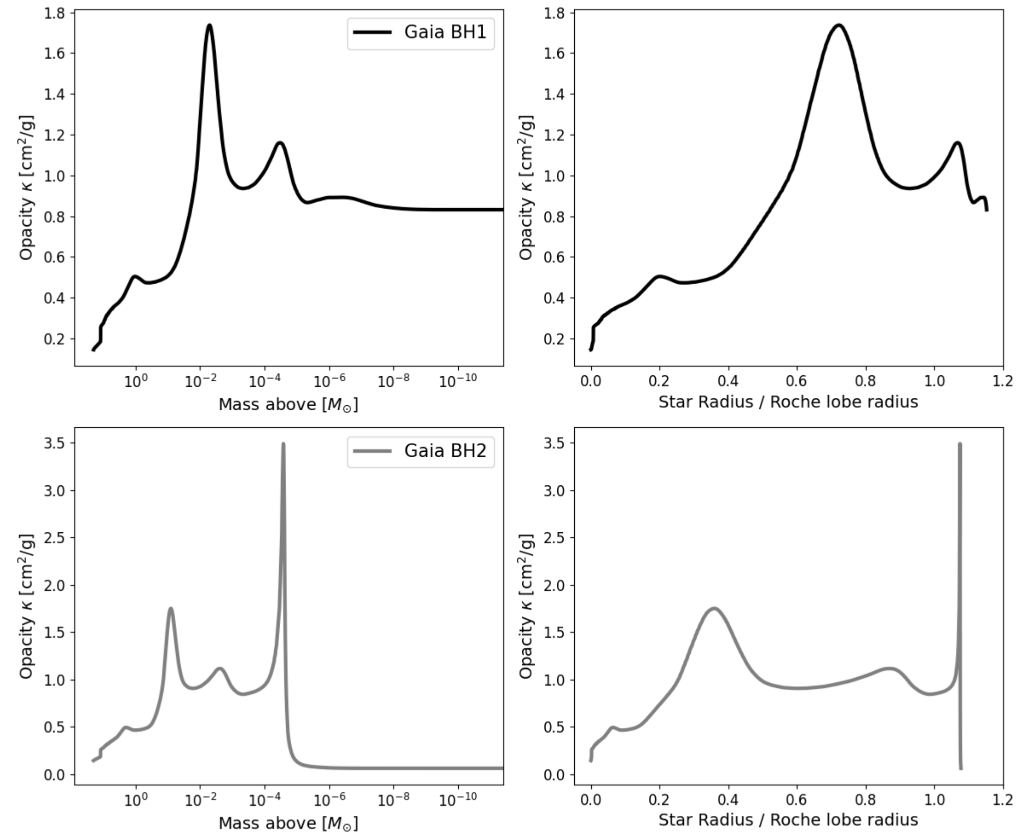

Figure 3. Opacity profiles of the donor stars at the early stages of RLOF from `MESA` simulations, shown as a function of mass above a given layer (left panels) and radius normalized by the stellar Roche-lobe radius (right panels). Results are shown for the Gaia BH1 progenitor system – upper panels, black line and the Gaia BH2 progenitor system – lower panels, grey line. For comparison, the Eddington opacity for the presented stars would be $\sim 1.66\,\mathrm{cm^2 g^{-1}}$ and $\sim 1.53\,\mathrm{cm^2 g^{-1}}$ for Gaia BH1 and BH2 respectively. Those opacity limits would be lower for a rotating star, as the additional centrifugal force reduces the effective gravity.

lar momentum of the donor's center of mass. Mass loss from the donor's vicinity is physically plausible in wide, unequal-mass binaries such as the studied progenitors of the Gaia BH systems due to: Roche-lobe sizes of the components, eruptive mass loss driven by the donor's high-opacity subsurface layers or donor's self accretion (as discussed in detail in Section 4). Although our prescription is idealized and likely does not capture, for example, the exact mass-loss rate, it provides a useful starting point, emphasizing that the true mass-loss process is likely more complex than what is typically implemented in most current binary evolution models. Below, we outline the caveats of this scenario and briefly discuss its potential implications for other populations of binary systems.

5.1. *Caveats*

In the presented evolutionary scenario, we assume that both components of the binary form simultaneously. In reality, however, the pre-main-sequence evolution of the low-mass companion may play an important role. For instance, the time required for a $1M_\odot$ star to reach the zero-age main sequence can be delayed by several megayears, which is comparable to the lifetime of its massive companion. During this phase, the stellar radius may be several times larger than on the main sequence (e.g., R. Kippenhahn et al. 2013; I. Baraffe et al. 2015), potentially leading to an episode of early mass transfer. Nevertheless, the formation of such systems at these early stages is likely more complex and may involve additional factors and processes, such as dynamical interactions.

Most popular prescriptions for non-conservative mass transfer in binary evolution assume that the lost mass carries the specific angular momentum of the accretor's center of mass. In this work, we instead adopt a model in which the ejected mass carries the specific angular momentum of the donor's center of mass. In reality, mass loss can occur through more complex geometries. Recent studies suggest that, under certain rapid mass-transfer conditions, some material may also escape through the L3 (behind the donor) or L2 (behind the accretor) Lagrange points (W. Lu et al. 2023; P. Scherbak et al. 2025). Such mass loss would carry substantially more angular momentum than that associated with the donor's center of mass. For the mass ratios considered here, where the donor is significantly more massive than the accretor, an L3 outflow is unlikely (S. H. Lubow & F. H. Shu 1975; P. P. Eggleton 1983; T. Ryu et al. 2025). Indeed, as illustrated in Figures 1 and 4, the L3 point remains unfilled throughout our simulations. A very small fraction of the total mass being lost through the outer Lagrangian point does not necessarily lead to instability (P. Marchant et al. 2021), but such cases should nonetheless be treated with caution.

All Gaia BH systems detected to date are eccentric, which may have influenced their mass-transfer evolution, depending on whether the eccentricity was inherited from earlier evolutionary stages or induced after BH formation. Possible origins of the eccentricity, as well as the potential to constrain factors such as natal kicks, are discussed in more detail in Appendix B.

Another potential caveat is that the progenitors of Gaia BH systems are often thought to lie within the regime of the so-called Darwin instability, in which tidal synchronization extracts angular momentum from the orbit and can potentially lead to a stellar merger (G. H. Darwin 1879; J. P. Zahn 1977; P. Hut 1980). Our `MESA` models include tidal interactions, and under our standard assumptions, the orbit expands efficiently in response to mass transfer, avoiding the Darwin instability. The ultimate fate of the system and the possibility of a merger, however, depend on the tidal prescription and the adopted tidal efficiency, which remain highly unconstrained.

5.2. *Broader implications*

If the mass-transfer model proposed here represents a realistic formation scenario for Gaia BH systems, it would have important implications for other binary populations. In particular, several classes of post-mass transfer systems exhibit similar puzzling orbital separation distributions that challenge standard binary evolution models. Full or partial mass loss with the specific angular momentum of the donor's center of mass could provide a plausible explanation for some of these systems. If a similar type of mass loss occurs—perhaps at lower efficiency—in more equal-mass or lower-mass binaries, it could significantly influence the predicted properties of all post-mass-transfer populations. Here, we provide a few illustrative examples.

Similar mass-loss may contribute to the formation of relatively wide white dwarf (N. Yamaguchi et al. 2025) and neutron star binaries (K. El-Badry et al. 2024) detected by Gaia. In these systems, the observed orbital periods, similarly to BH systems, challenge standard isolated binary evolution scenarios and the CE scenario.

Another intriguing class of systems that appear inconsistent with predictions from standard binary evolution models are the stripped Wolf–Rayet stars observed in the Small Magellanic Cloud (A. Schootemeijer et al. 2024). Monitoring of seven known cases led to the surprising conclusion that none host a close, massive companion capable of removing the hydrogen envelope. Given the relatively low metallicity of the Small Magellanic Cloud, purely wind-driven mass loss would be insufficient to strip the envelope unless enhanced by eruptive episodes. We argue that, although the survey ruled out massive, close companions, these stripped Wolf–Rayet stars may still harbor low-mass companions on wide orbits. In our scenario, radial velocities of post-mass-transfer stripped helium stars are of order $\sim$ 4–8 km s^{-1}. A. Schootemeijer et al. (2024) found low radial-velocity variations between 6 and 23 km s^{-1} (median standard deviation of 5 km s^{-1}) for the seven Wolf–Rayet stars, suggesting that systems with low-mass companions could remain undetected due to similarly small velocity amplitudes. We speculate that, analogous to the progenitors of Gaia BH systems, these stars may have undergone a similar episode of orbital widening during a past RLOF phase.

The presented mass loss scenario may also have important implications for the formation of low-mass X-ray binaries with BH companions, potentially helping to resolve one of the long-standing challenges in their evolutionary formation. In traditional CE channels, the BH progenitor's envelope is typically too tightly bound to allow successful envelope ejection, preventing the survival of the observed binary systems (V. Kalogera 1999; P. Podsiadlowski et al. 2003; G. Wiktorowicz et al. 2014; C. Wang et al. 2016). In the presented evolution, the donor can expand significantly during (Fig. 1 and Fig. 4). For systems with initially wider orbital periods than studied here, progenitors of Gaia BH binaries, further orbital expansion during mass loss can lead to the development of a deep convective envelope in the donor. This may trigger a delayed CE phase. However, at this stage, the donor might have already lost a significant fraction of its envelope during the preceding mass loss phase. Consequently, the ejection of the remaining envelope could be facilitated.

If such a mass-loss mechanism operates, it would likely also influence the formation and predicted mass distributions of binary compact object mergers detected via gravitational waves, particularly those formed through isolated binary evolution involving mass-transfer interactions (K. Belczynski et al. 2020; S. S. Bavera et al. 2021; A. Olejak et al. 2021; L. A. C. van Son et al. 2022; A. Picco et al. 2024; J. Klencki et al. 2025). A notable example of a potential gravitational-wave progenitor is the ultraluminous X-ray source P13 in NGC 7793 (M. Bachetti et al. 2014; C. Motch et al. 2014; F. Fürst et al. 2016). This ULX binary consists of a massive late-B supergiant donor ($\sim$ 18–23 $M_{\odot}$) and a neutron star accretor ($\sim 1.4\,M_{\odot}$), exhibiting super-Eddington accretion. Despite the extreme mass ratio of $M_{\rm don}/M_{\rm acc} \approx 20$, the system appears to sustain stable mass transfer, implying reduced angular momentum loss, consistent with the scenario we propose for our Gaia BH progenitor systems with similar mass ratios.

The next planned step is to develop and implement physical models within binary population synthesis frameworks to assess their broader impact on different populations. Incorporating this effect into rapid population synthesis properly is, however, challenging as it likely affects primarily a specific subset of systems—for example, those in particular mass, mass-ratio, orbital periods or metallicity regimes—depending on the underlying, still-speculative physical mechanism (or synergy of different factors). Future work should include high-resolution hydrodynamical simulations, more realistic modeling of the mass-loss stream that accounts, e.g., for self-accretion (D. D. Hendriks & R. G. Izzard 2023), combined with additional observational constraints from diverse binary populations, to test the plausibility and efficiency of the proposed mass-loss geometry. Upcoming Gaia data releases, in combination with complementary surveys, will be crucial for testing these models and further constraining the physical processes that govern binary evolution in the Galaxy and beyond.

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Software: Python matplotlib, `MESA`

APPENDIX

A. APPENDIX INFORMATION

Figure 4 shows an example evolutionary track leading to a system with final properties (masses, orbital separation) equivalent to Gaia BH2. The top panel displays the evolution of the donor's mass; the middle panel shows the evolution of the donor's radius; and the bottom panel presents the evolution of the orbital period. The timescale is expressed as the logarithm of the remaining time until the end of evolution, defined as the point of central helium depletion.

The initial binary system consists of a $20\,{\rm M}_{\odot}$ BH progenitor and a $1\,{\rm M}_{\odot}$ companion in an orbit with a period of 260 days, corresponding to a separation of $\sim 475\,{\rm R}_{\odot}$. After approximately 9 Myr, the primary evolves off the main sequence and undergoes significant radial expansion, triggering a short but intense mass transfer episode lasting ~ 0.1 Myr, with a peak mass transfer rate of $3.3 \times 10^{-3}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$. However, as shown in the middle panel of Figure 4, the outer Lagrange point L3, behind the donor, is never filled.

$(R_{\star} - R_{\rm L1})/R_{\star}$

As a consequence of the mass transfer, the orbital period increases from 260 to ~ 850 days, while the donor rapidly loses nearly $10\,{\rm M}_{\odot}$, stripping away most of its hydrogen-rich envelope.

Following this, the donor's radius contracts, and for over ~ 0.4 Myr the star detaches from its Roche lobe, halting mass transfer. At final stages of He burning, the star expands once more, initiating a second mass transfer episode lasting ~ 0.2 Myr. This phase proceeds at a significantly lower rate, $\sim 10^{-6}$–$10^{-4}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$, and results in the loss of an additional $\sim 1\,{\rm M}_{\odot}$. Ultimately, the mass transfer ceases, leaving behind a $\sim 9\,{\rm M}_{\odot}$ helium core and a low-mass companion in a widened orbit with a period of ~ 1135 days.

B. ECCENTRICITY

Both Gaia BH1 and BH2 systems are eccentric (see Tab. 1). Formation of BHs with their final masses of $\sim 9 - 10\,{\rm M}_{\odot}$ is highly uncertain. Since low mass BHs could form either via successful or failed supernova explosion - so-called direct

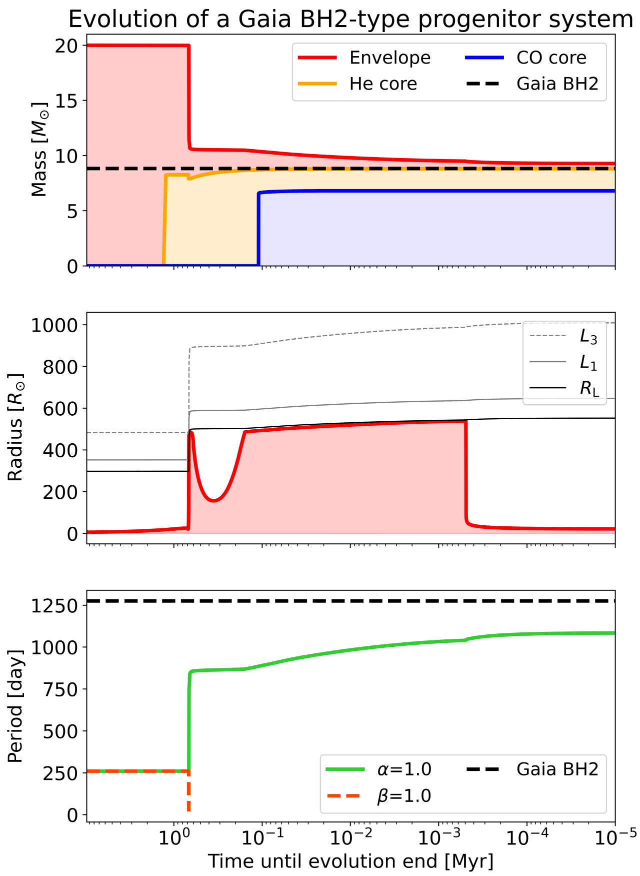

Figure 4. Evolution of the progenitor system of Gaia BH2. The physical assumption and figure description are the same as for Figure 1.

collapse of the core (C. L. Fryer et al. 2012; M. Ugliano et al. 2012; A. Burrows et al. 2020; R. A. Patton & T. Sukhbold 2020), the eccentricity in the binaries may originate from multiple alternative mechanisms, which we briefly comment below:

- *Initial eccentricity:* The progenitor binary could have formed with a non-zero eccentricity, which might be only partially damped if tidal circularization was inefficient. Both observations (G.-M. Oomen et al. 2018, 2020; A. Escorza et al. 2020; J. Müller-Horn et al. 2025) and theretical modeling (K. A. Rocha et al. 2025; A. Parkosidis et al. 2025) suggests wide binaries can remain eccentric after mass transfer phase.

- *Asymmetric mass loss* may result in a natal kick imparted to the newly formed BH (tens of km s^{-1}) which efficiently induce orbital eccentricity (V. Kalogera 1996). One can determine orbital parameters after the BH formation using equations B1 and B2, for system separation and eccentricity, respectively (T. M. Tauris 2022).

$$\frac{a_{\rm post}}{a_{\rm pre}} = \left[2 - \frac{M_{\rm pre}}{M_{\rm post}} \left(\frac{v_r^2 + v_{\rm p}^2 + (V_{\rm pre} + v_{\rm t})^2}{V_{\rm pre}^2}\right)\right]^{-1} \tag{B1}$$

$$1 - e^2 = \frac{M_{\rm pre}}{M_{\rm post}} \cdot \frac{a_{\rm pre}}{a_{\rm post}} \cdot \frac{v_{\rm p}^2 + (V_{\rm pre} + v_{\rm t})^2}{V_{\rm pre}^2} \tag{B2}$$

Where: $a_{\rm pre}$ and $a_{\rm post}$ are the semi-major axes before and after a BH formation, e is the resulting eccentricity, $M_{\rm pre}$ and $M_{\rm post}$ are the total system masses before and after a BH formation, $V_{\rm pre}$ is the relative orbital velocity before a BH formation. The natal kick vector v consists of components in the radial v_r), tangential v_t, and polar v_p directions within the frame of reference of the exploding star.

Since our model is flexible regarding the pre-supernova orbital parameters: separation and eccentricity, ejected masses and its direction, it is possible to reproduce the observed parameters for a variety of different initial assumptions. As an example, we can assume that the ejected mass to be $\Delta M = 0.5$ M$_\odot$, consistent with a complete collapse scenario and mass loss only in the neutrino stream (e.g., C. L. Fryer 1999; C. L. Fryer et al. 2012; H. T. Janka & D. Kresse 2024) and that the system's orbit was circular before a BH formation.

For a Gaia BH1 type of system, aiming to reach an eccentricity of ≈ 0.4 and a final orbital period of ≈ 180 days we can adopt for example: a radial kick of ≈ 35 km s^{-1} with a pre-SN orbital period of ≈ 130 days or a tangential kick of ≈ 15 km s^{-1} with a pre-SN orbital period of ~ 90 days or a polar kick of ≈ 62 km s^{-1} with a pre-SN orbital period of ≈ 85 days

For Gaia BH2 type of system, targeting slightly higher an eccentricity of ≈ 0.5 and significantly wider orbital period of ≈ 1200 days we can find solutions: a radial kick of ≈ 25 kms^{-1} with a pre-SN orbital period of ≈ 700 days, a tangential kick of $\approx$12 km s^{-1} with a pre-SN orbital period of ≈ 450 days or a polar kick of ≈ 40 kms^{-1} with a pre-SN orbital period of ≈ 450 days.

The presented cases are just to build intuition, and the real natal kick would be combinations of those three variants.

- *Symmetric mass loss:* Also, large spherically symmetric mass loss during BH formation can induce eccentricity via the so-called Blaauw kick, which can be estimated as (A. Blaauw 1961):

$$e = \frac{M_{\rm pre} - M_{\rm post}}{M_{\rm post}} \tag{B3}$$

  Where: $M_{\rm pre}$ is the total mass of the binary before the supernova, $M_{\rm post}$ is the total mass after the supernova. Reproducing the observed values ($e \approx 0.45$ for BH1 and $e \approx 0.52$ for BH2) would require substantial mass loss of $\sim$4–5 $M_\odot$.

- *Dynamical interactions:* Post-formation interactions—such as the presence of a distant tertiary companion—could increase the eccentricity through secular perturbations (Kozai–Lidov cycles, see e.g., C. Shariat et al. 2023). However, such scenarios require specific hierarchical triple configurations.

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