# Effects of the Common Envelope Phase on Binary Black Hole Evolution


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## Abstract


The detection of gravitational wave signals from binary black hole (BBH) mergers in recent years has raised pressing questions about the formation and characteristics of these systems. In order for BBHs produced in the traditional formation channel to merge in a Hubble time, the pair must undergo a common envelope (CE) phase to dramatically reduce the separation distance of the progenitors prior to CE ejection. Recent work on the CE phase has shown that density gradients in the envelope material produce a significant departure from drag and accretion rates of the embedded compact object as predicted by Hoyle-Lyttleton accretion (HLA) formalism; these effects, in turn, have implications for mass and angular momentum transfer between the donor star and compact object. Using a range of simplified progenitor systems in which a massive, stellar-mass black hole (BH) dynamically inspirals through the envelope of a giant stellar companion, we examine these CE effects.


## Motivation

With a growing number of LIGO detections of merging massive, stellar-mass BHs, the mechanisms by which close binaries are formed that are comprised of such BHs are of great interest. Pathways under investigation include the dynamical formation channel, in which preexisting BHs form a close binary through a chain of gravitational interactions in a densely populated cluster, and the traditional formation channel, in which a binary forms and evolves in isolation [1].

In the traditional channel, the progenitor stars in a binary cannot form close enough to merge in a Hubble time without a CE phase to tighten their orbit. However, this phase can result in a range of post-CE configurations. To understand the viability of the traditional channel for the formation of LIGO BBHs, we must understand how the CE phase affects binary evolution.

## Background

Broadly, the CE phase can be defined as the evolutionary stage in which a binary orbits within a shared envelope. For systems in which the primary is much more massive than the compact secondary (Fig. 1a), this occurs when the primary enters the giant branch and expands to the orbit of the secondary. Interactions with the envelope material cause the secondary to inspiral toward the core (Fig. 1b), depositing energy as it goes. If this energy is sufficient, the envelope will become unbound and lift away, leaving the compact object and core of the primary in a reduced orbit (Fig. 1c). If the envelope cannot be ejected, the secondary will merge with the core of the primary (Fig. 1d).

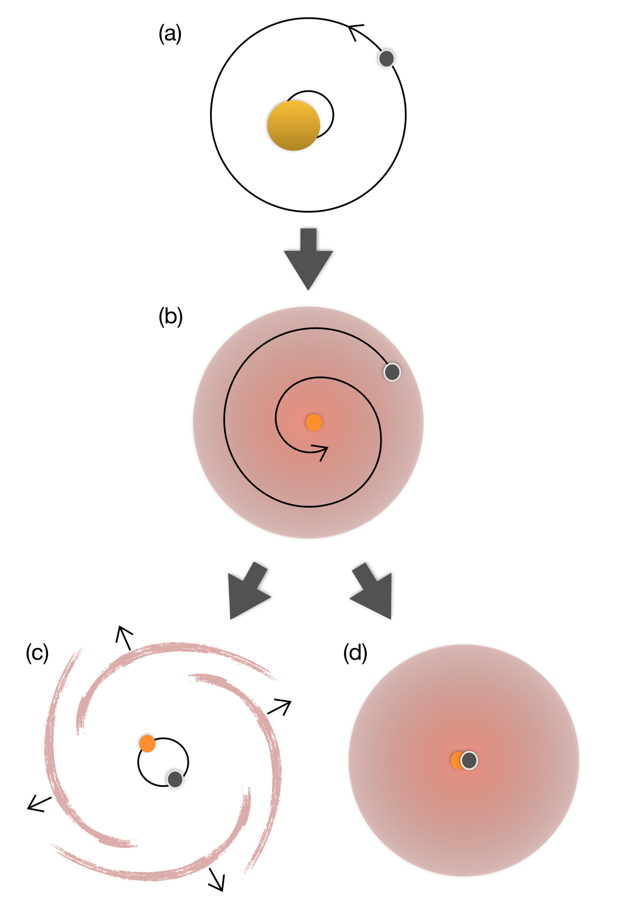


**Figure 1.** A typical sequence of CE evolution for a primary much more massive than the secondary. When (a) the main sequence primary of the binary evolves to (b) the giant branch, its expanding envelope engulfs the secondary, which will begin to inspiral. Interactions during the CE phase determine the outcome of the binary: if (c) the envelope is ejected, binarity will be retained, but if there is not enough energy to eject the envelope, (d) the secondary will merge with the core of the extended primary.

We are interested in systems in which the binary survives in a close enough orbit to merge within a Hubble time. For systems in which the secondary has a significant fraction of the mass of the primary, the orbital energy deposited in the envelope is sufficient for ejection at large separation, yet we have detected mergers of BBHs with mass ratios of order unity: the energy criterion alone does not define the final configuration.

We must compare the timescale of the inspiral, which depends on dynamical friction between the embedded BH and the envelope material, with that of energy sharing within the envelope.

## Envelope Structure and Drag

Traditionally, the formalism for a non-global treatment of CE drag and accretion is based on that of Hoyle-Lyttleton [2], in which the embedded object orbiting within the CE is approximated as a point mass centered in a supersonic gas flow of uniform density (Fig. 2a). A bow shock forms around the point mass, and gas that crosses the shock loses energy and forms a wake. Oncoming material within a certain vertical distance from the point mass will have its trajectory altered by gravitational attraction and meet material from the opposite side in the wake where it undergoes momentum cancellation due to symmetry. The accretion radius is defined as the vertical height within which inflowing material will stall behind the point mass and accrete:

$$R_a = \frac{2GM_{bh}}{v_\infty^2}.$$

Resulting increased density in the wake causes a gravitational drag force which leads to the inspiral of the embedded object.

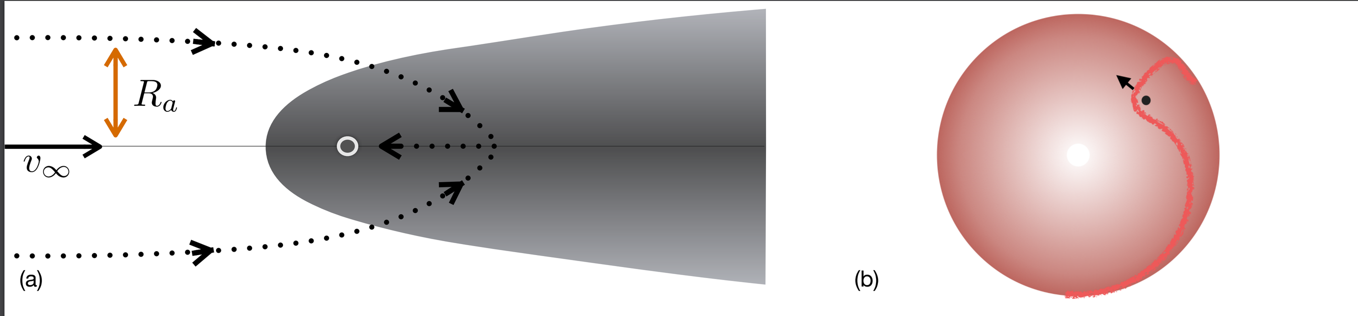


**Figure 2.** A basic schematic of Hoyle-Lyttleton accretion is shown in Panel (a). A centered point mass passes through oncoming flow of uniform density from the left at supersonic speed. A bow shock forms upstream (left) of the point mass, with a wake forming downstream (right). Material within the accretion radius $R_a$ will gravitationally interact with the point mass as shown by the particle path, stalling behind it due to symmetry, and either accreting or contributing to dynamical friction. In Panel (b), adapted from MacLeod & Ramirez-Ruiz 2015a, the same shock structure is shown within a stellar envelope with a density gradient. With broken symmetry, the properties of the inspiral process are altered.

Recent work has shown that the introduction of a density gradient in the oncoming flow can significantly alter the drag force and accretion rates found in HLA formalism [3,4,5]. Though the bow shock of HLA is retained, the symmetry is broken (Fig. 2b), leading to increased turbulence and a reduction in accretion [3,4]. In addition, dynamical friction experienced by the embedded object is enhanced with increasing density gradient due to the effects of denser material dredged up from 1 $R_a$ below. This may accelerate the early stages of the common envelope phase and lead to a much quicker inspiral [5].

The introduction of drag coefficients $C_d$ that scale the HLA drag force to account for the density gradient effects allows a relatively simple calculation method for exploring the intersection of timescales and other criteria for CE ejection. We use this formalism here.

## Energy Criterion

Previous work on the CE phase has often assumed instantaneous energy transfer within the envelope, so that inspiral is said to end at the separation distance $r$ that accounts for enough transfer of orbital energy to unbind the envelope [6]. This "parking" prescription is sufficient in low mass ratio binaries, but not necessarily those of recently detected LIGO BBHs, which require mass ratios of $q$~0.2-0.5 at the onset of the CE phase. Mass ratios in this regime generally transfer enough energy to unbind the envelope (from $r$-$R_a$ outward) at large $r$ (Fig. 3), preventing a merger within a Hubble time. Evidence of such mergers suggests the inspiral must progress on a dynamical timescale which outpaces energy sharing in the envelope.

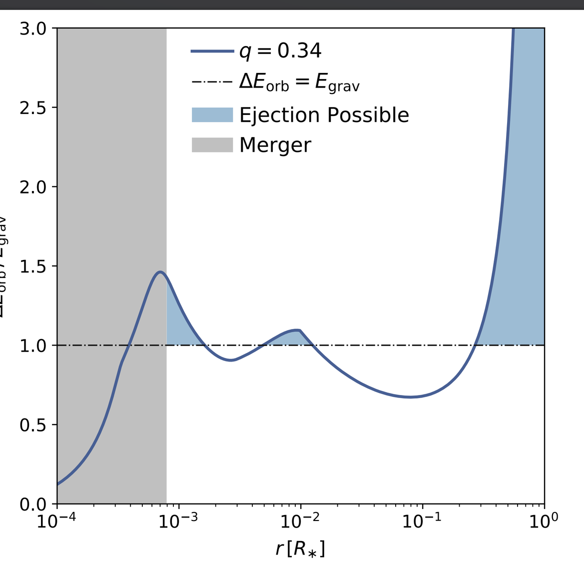


**Figure 3.** Ratio of the change in orbital energy of the embedded black hole to the gravitational binding energy of the envelope as a function of radius in an 88 $M_\odot$ primary with $q = M_{bh}/M^* = 0.34$. Shaded blue regions meet the energy criterion for envelope ejection. The shaded grey region lies within the core boundary. If the orbit of the black hole decays slowly in the outer 3/4 of the envelope, it is very likely it will eject the surrounding material and "park" too far away to merge.

## Comparison of Timescales

To illustrate the nontrivial role of drag from density gradients in the formation of massive, stellar-mass BBHs, we compare the timescales that result from both the HLA formalism and that of MacLeod et al. and demonstrate the effects on inspiral. The accretion radius $R_a$ is a useful scale height because the black hole must inspiral ~1 $R_a$ per orbit to interact with essentially unperturbed envelope material, and in turn continue its inspiral. We define our timescales as follows:

$$\tau_{\rm insp} = \frac{R_a}{|v_r|} \qquad \frac{\pi r}{v_\infty} \leq \tau_{\rm energy} \leq \frac{\pi r}{c_s}$$

in which $\tau_{\rm insp}$ is the time required to travel inward 1 $R_a$ as measured at $r$, and $\tau_{\rm energy}$ is a simple energy sharing time through a shell of material at $r$. Figure 4 shows a comparison of these values with both approaches. Where the ratio of these is greater than 1, energy is shared faster than inspiral occurs, making envelope ejection and "parking" near $r$ likely. Where the ratio is less than 1, the black hole plunges in faster than the envelope can react to the deposited energy and inspiral continues.

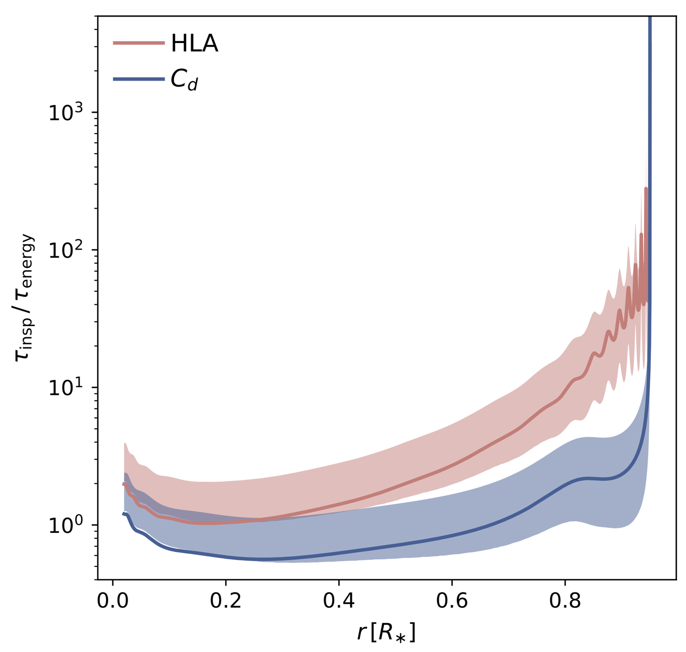


**Figure 4.** Timescale ratio as a function of $r$ for an 88 $M_\odot$ primary with an embedded black hole of $q = 0.34$. The shaded regions correspond to the range of energy sharing times corresponding to sound speed $c_s$ through orbital speed $v_\infty$. The dark lines represent the curves of inspiral timescale normalized by the orbital period at $r$. Note that the HLA result is much greater than 1 in the outer portion of the envelope, suggesting that envelope ejection at large $r$ will occur since the energy criterion is met and the envelope has ample time to react. However, results from use of the drag coefficients $C_d$ are near or below 1 for most of the inspiral, then increase slightly upon approaching the dense core region. This indicates that even if the energy criterion is met in the outer regions, inspiral is more likely to stop deep in the interior where both the timescales are favorable and the energy criterion is met.

Taking the minimum values of this ratio as a limit with and without use of the drag coefficients, we can plot limiting cases of the inspiral during the CE phase (Fig. 5). In Figure 5a, due to the timescale ratio greater than 1, the envelope from $r$-$Ra$ outward will be ejected no deeper than ~0.25$R_*$. In Figure 5b, due to timescale ratio less than 1, the envelope will be ejected at most ~0.05$R_*$, leaving a much closer binary. These preliminary findings indicate that the inclusion of the effects of density gradient in the CE phase is instrumental in understanding the conditions that determine the configuration of post-CE binaries.

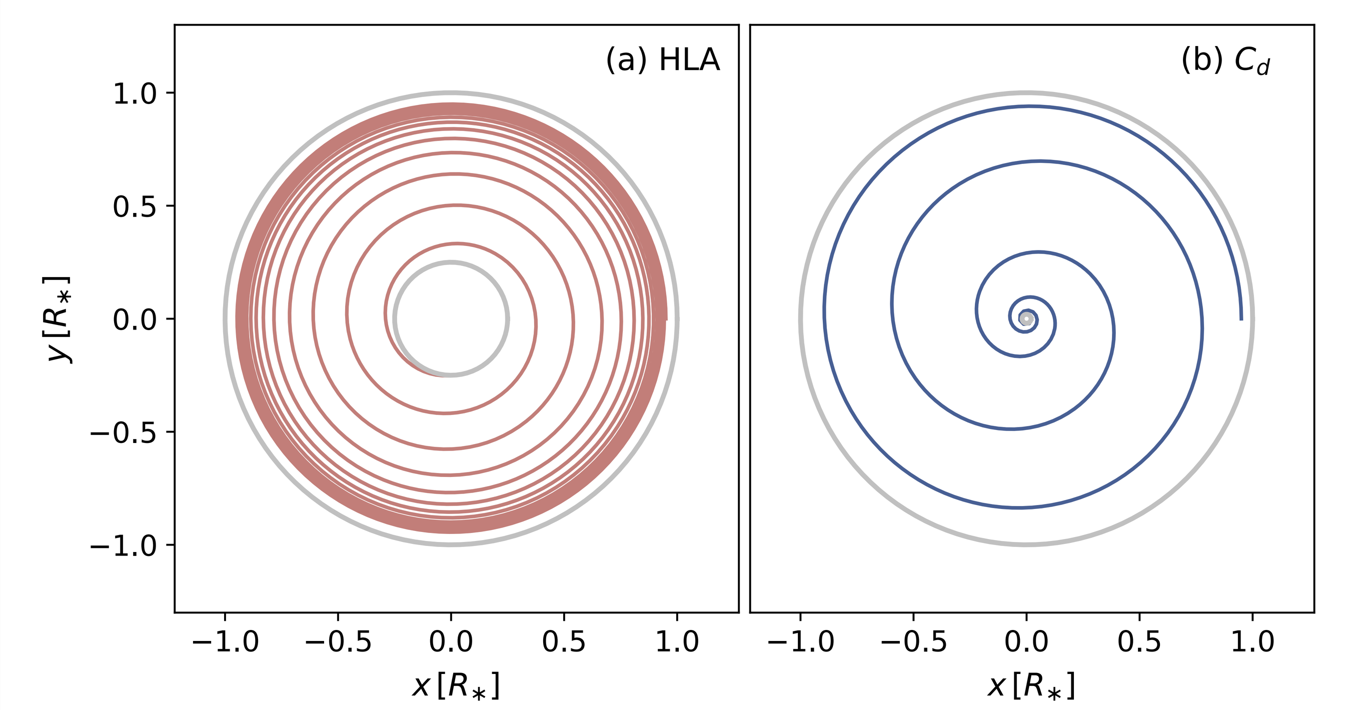


**Figure 5.** Limiting cases of inspiral using the (a) HLA formalism and (b) applying drag coefficients $C_d$ in an 88 $M_\odot$ primary with an embedded black hole of $q = 0.34$. In Panel (a) where the ratio $\tau_{\rm insp}/\tau_{\rm energy}$ is much greater than 1, orbits are tightly wound and interact with the same envelope material many times. The energy criteria are fulfilled throughout the shown inspiral, as well as timescale ratios favorable (especially in the outer region) to envelope ejection, so the small grey circle shows maximum possible penetration. Panel (b) shows the result of a timescale ratio less than 1 through nearly all of the envelope, and stops when the ratio becomes greater than 1 and energy sharing speed overtakes the descent speed and ejection is again possible. Based on these two criteria, the addition of drag coefficients to the HLA formalism gives physical conditions for the end of the CE phase while creating the close binaries necessary for a merger to occur in a Hubble time.

## Future Work

Next steps include performing similar analyses for a range of progenitor masses and $q$ values to investigate whether testable predictions about post-CE binary configuration can be made that are unique to the traditional formation channel. We will also explore possible implications of the inclusion of drag coefficients for final BH spin and mass accretion.


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