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 from 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 interacts 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 BBHs, 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).

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 separations, 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 accreting 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 must 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 infalling material will still bear the point mass and accrete.

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 encountered in the envelope (Fig. 2c). 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 CE criteria for 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 $r$ outward) at large $r$, 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.

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 $\sim R_a$ per orbit to interact with essentially unperturbed envelope material, and in turn continue its inspiral. We define our timescales as follows:

$$T_{insp} = \frac{R_a}{\nu_{	ext{insp}}}$$

in which $T_{insp}$ is the time required to travel inward $1 R_a$ as measured at $r$, and $\nu_{	ext{insp}}$ is a component 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” $r$ unlikely. 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.

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 Fig. 5a, due to the timescale ratio greater than 1, the envelope from $r$-$R_a$ outward will be ejected no deeper than $-0.25 R_a$, 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.

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.

References


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