Convection in Common Envelopes

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Convection in Common Envelopes

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Contents

1 Introduction 1

1.1 Common Envelopes .............................................. 2
1.2 Modelling Convection in CEs .................................. 5
  1.2.1 Convective Simulation Techniques ........................ 5
  1.2.2 The Employed Convection-Energy Model .................. 6
1.3 Current Research and Major Issues ............................ 8

2 Methodology 10

2.1 Determining Convective Regions ............................... 13
2.2 Energy and Luminosity Considerations ........................ 15
  2.2.1 Energy Conservation ...................................... 15
  2.2.2 Luminosity Requirements ................................. 18
2.3 Outcomes of Common Envelope Interactions .................... 20

3 Ejection Efficiency in Convective Regions 21

3.1 Variability of the SCCR ....................................... 25
3.2 Ejection Efficiency, \( \bar{\alpha}_{\text{eff}} \) .......................... 28

4 Discussion 30

4.1 Implications of Convection .................................... 33

5 Conclusions and future directions 35
Abstract

The outcomes of stellar evolution can be significantly affected by the presence of close substellar or stellar companions. Common envelopes (CE) are thought to be the main channel for producing close binaries in the universe and occur when an orbiting companion is engulfed in the outer layers of the primary’s envelope. CE outcomes are dependent on the fraction of energy from the decaying orbit that can contribute to ejecting the envelope, often defined via an efficiency, $\bar{\alpha}_{\text{eff}}$. The post-CE orbital separations and periods can then be determined given knowledge of the binding energy of the primary’s envelope.

In this work, detailed stellar interior models of primaries at their maximum evolved radius are used to calculate $\bar{\alpha}_{\text{eff}}$ for unique primary-companion mass pairs. Properties of the surface-contact convective region (SCCR), and its variability, are shown to affect the ejection efficiency since in these regions the energy released during inspiral can be carried to the stellar surface and radiated away. The ejection failure seen in numerical simulations may be resolved with a proper treatment of convection, whereby the binary orbit shrinks before energy can be tapped to drive ejection. With the inclusion of convection, we find post-CE orbital periods of less than a day which is an observed phenomenon infrequently achieved by population studies with a constant $\bar{\alpha}_{\text{eff}}$. A prescription for calculating $\bar{\alpha}_{\text{eff}}$ given knowledge of SCCR properties is provided.
1 Introduction

A star spends most of its life on the main-sequence, during which hydrogen fusion maintains a stable star. After all of the core’s hydrogen has been fused into helium, a shell of hydrogen surrounding that core begins to fuse, and the star climbs the Red Giant Branch (RGB). On the RGB, the star can expand to hundreds of times its original radius, during which the extended volume of the star may begin to tidally interact with surrounding bodies. Also during this time, the star experiences more internal hydrogen and helium burning processes. The burning of core helium on the Zero-Age Horizontal Branch (ZAHB) occurs simultaneously with hydrogen shell burning. When the hydrogen shell is fused to helium and the core is fused to carbon and oxygen, the star begins its ascent up the Asymptotic Giant Branch (AGB). The star can expand, yet again, to over hundreds of times its main-sequence radius and similarly begin to tidally interact with surrounding bodies, such as binary companions.1 These interactions are the predominant proposed pathway for producing compact binary systems observed in the Universe (Toonen and Nelemans, 2013; Kruckow et al., 2018; Canals et al., 2018), though other mechanisms have also been proposed (Fabrycky and Tremaine, 2007; Thompson, 2011; Shappee and Thompson, 2013; Michaely and Perets, 2016).

Thermal pulses occur while the AGB star’s radius grows; the spherical shell of helium that surrounds the carbon and oxygen core experiences a thermonuclear flash, which causes the radius of the star to spike before re-stabilizing. During each of these thermal pulses, the outer-most convective zone contracts and expands, pulling elements from deep within the AGB star to the surface. This dredge-up process has been shown to be important for the formation of carbon stars and is responsible for the observable surface abundance of elements. Transport of stellar material and interior energy to the

1For stars with masses greater than or equal to $1.4M_\odot$, the radius of the star on the AGB is greater than the RGB. In these cases, the chance of interaction with the star on the AGB is greater than when the star is on the RGB (Nordhaus et al., 2010; Nordhaus and Spiegel, 2013).
surface of the star via convection is an idea that has been discussed in the literature, and will be described in detail in future sections.

1.1 Common Envelopes

First proposed by Paczynski (1976), common envelopes (CEs) occur when the primary star in a binary system evolves from a main-sequence star to a giant star and interacts with the secondary (Ivanova et al., 2013; Kochanek et al., 2014). Possible interactions that lead to CEs are direct engulfment (the radius of the giant star surpasses the orbital radius of the companion), Roche Lobe overflow, or decay of the orbit via tidal dissipation (Nordhaus and Blackman, 2006; Nordhaus et al., 2010; Chen et al., 2017). For a short time, only 10s to 1000s of years (Ivanova et al., 2013), the two stars orbit within a shared envelope. Given sufficient energy transfer from the engulfed companion to the outer layers of the primary, the envelope can become unbound from the primary and then ejected from the system.

Ejection of the envelope is not guaranteed. Energy and angular momentum are transferred during the CE phase as the companion inspirals through the layers of the primary (Iben and Livio, 1993). If the energy transferred from the inspiraling companion exceeds the energy required to unbind the outer layers of the primary, the envelope may be ejected from the system, leaving a short-period binary with at least one compact object. If the envelope cannot be ejected, the interaction results in a “single” star, as the companion is destroyed in the process. Due to the binary interaction, this single star may now experience alternate evolutionary tracks (Nordhaus et al., 2011).

Details of CE systems, like mass ratio, initial orbital separation, and internal properties of the giant star have been shown to affect the likelihood of certain evolutionary pathways (e.g., De Marco et al. 2011; Zorotovic et al. 2011; Politano and Weiler 2007). The internal properties of AGB stars include deep convective envelopes, which
may affect the outcomes of interactions with binary companions. As shown in Figure 1, the convective zones (green) encompass much of the AGB star’s outer mass. These zones also change over time, i.e. during the thermal pulses of the star. The effect of large convective zones in CE primaries and their corresponding system ejection efficiencies remain a topic of active research.

Figure 1: Internal structure of an AGB star during a late thermal pulse. The red solid line corresponds to the mass-coordinate of the H-free core. The solid green shaded section shows the convective region in the envelope (Herwig, 2005).

The CE can result in one of several possible outcomes, with some shown in Figure 2. The resulting compact objects in short-period orbits possible via CE evolution have piqued the interest of astronomers, especially with the recent gravitational wave detections from such pairs, like the neutron star-neutron star merger observed in 2017 (Abbott et al., 2017). An understanding of the processes that lead to close, compact object binaries is an area of active research as the search continues for gravitational waves, from binary black hole – and now binary neutron star – mergers.
Figure 2: Outcomes of CE interactions as described by Ivanova et al. (2013). The three columns describe three potential paths to compact objects in binaries. The left column describes two scenarios that can potentially produce Type Ia supernovae. The center column shows a CE evolutionary track that results in a milli-second pulsar (MSP) and white dwarf (WD) binary. The right column shows a potential track to produce a neutron star pair binary. These evolutionary tracks are not exhaustive.
1.2 Modelling Convection in CEs

1.2.1 Convective Simulation Techniques

The standard computational method to simulate convection within stars is through mixing length theory (MLT) which allows a single convective eddy to move through a scale height within a convective region (Herwig 2005 and references therein). The convective cell then acts as an “average” cell and the spectrum of turbulence is ignored. The average eddy, driven by buoyancy, moves a distance $\Lambda$ before dissipating. The variable $\Lambda$ is the mixing length, given by

$$\Lambda = \alpha H_P = \alpha \left( -\frac{\mathrm{d} \ln P}{\mathrm{d} r} \right)^{-1},$$

(1)

where $\alpha$ is of order unity (calibrated to Solar quantities), $P$ is the radial pressure within the star, and $H$ is a pressure scale height, a quantity that defines the distance over which the pressure changes by a fraction of itself. From this mixing length, a convective velocity for each mass can be determined by balancing the kinetic energy per mass and the work done by buoyancy, ultimately yielding

$$\bar{v}_{\text{conv}} = \sqrt{\frac{\Delta \rho |g|}{8 \rho \Lambda}}.$$

(2)

This describes the average radial convective velocity of an average eddy motion described by MLT (Cox and Giuli, 1968)\(^2\).

An alternate method, described by Henyey et al. (1965), modifies MLT to consider the convective efficiency, that is the opacity of the convective eddies, as variable. This efficiency parameter allows in some cases, especially in simulations, for radiation from the outer layers of the star. This alternate convective method is modeled through a

\(^2\)MLT as described by Cox and Giuli 1968 is used by the stellar evolution code in this work.
modified adiabatic gradient which accounts for pressure from turbulence of the medium.

Yet another, more computationally expensive, method is the Full Spectrum of Turbulence (FST) convective model which uses up to millions of these convective eddies to simulate convection. In this model, turbulent flux, a component of total stellar flux, is a function of the difference in the temperature gradient and the adiabatic temperature gradient, and consequently always greater than the MLT-prescribed convective flux. The more significant difference of FST as compared to MLT is the treatment of scale height, and thus convective eddies. MLT “stacks” convective eddies, assuming that the they are smallest near the stellar surface and increase toward the core (as necessitated by \( H_P \)); FST acknowledges the nonlinear, compressible nature of convective eddies and includes them in virtual “stacking” of convective eddies throughout the energy spectrum (Canuto and Mazzitelli, 1991).

1.2.2 The Employed Convection-Energy Model

Some authors have suggested the inclusion of alternate energy sources to have CE events ending in short-period binaries. Instead of adding energy sources, we employ a model in which the large convective envelope of RGB/AGB stars can carry liberated energy from the companion’s decaying orbit away from the system just as the convective processes carry elements to the surface, as observed by surface element abundances. A schematic cartoon of this model is shown in Figure 3.

In a common envelope system, a companion body brushes the surface of the primary and experiences a sort of drag force which slows its orbit. The slowing velocity forces the companion to assume a smaller orbital radius. This change in radius releases orbital energy. In this convection model, as the companion body inspirals within a convective region that contacts the surface of the primary star, the released orbital energy can be carried to the surface and radiated away. Therefore, we assume that the
Figure 3: A cartoon describing the convective model used in this work. Top: as the companion (black circle) inspirals through the primary, it first plunges through the surface-contact convective region (SCCR). The convective eddies (purple ovals) can carry liberated energy from the companion’s decaying orbit to the surface where they are radiated away. Bottom: after the companion inspirals beyond the SCCR, the energy it releases can be fully transferred into the primary, aiding envelope ejection.
transfer of energy in these regions is 0% efficient; the energy liberated by the decaying orbit cannot contribute to ejecting the envelope. In contrast, in non-convective regions, the liberated energy contributes to unbinding the envelope. The energy transfer in the non-convective regions is therefore assumed to be 100% efficient. With this model, energy transfer within the star is different from traditional fully efficient energy transfer models, but still does not tap alternate energy sources.

1.3 Current Research and Major Issues

A popular way of predicting common envelope outcomes and thus the consequent populations is by employing an “α-formalism.” This allows for an ejection efficiency, $\bar{\alpha}_{\text{eff}}$, to be defined based on energy arguments, typically via:

$$\bar{\alpha}_{\text{eff}} = \frac{E_{\text{bind}}}{\Delta E_{\text{orb}}}.$$  

Here, the energy that is required to unbind layers from the primary star is $E_{\text{bind}}$ and the energy liberated from the decaying orbit of the secondary body is $\Delta E_{\text{orb}}$ (for a complete discussion see Sec 2.2.1; Tutukov and Yungelson 1979; Iben, I. and Tutukov 1984; Webbink 1984; Livio and Soker 1988; De Marco et al. 2011). An ejection efficiency in combination with the primary’s binding energy can yield predictions for the ultimate orbital separations of the system. These predictions are highly sensitive to assumed values of energy transfer efficiency, since it is not 100% efficient (Claeys et al., 2014). Therefore constraining $\bar{\alpha}_{\text{eff}}$ through theory and observations is necessary and a topic of active research. The ejection efficiency is also often assumed to be constant across different systems (i.e., universal) for simplicity, so relating $\bar{\alpha}_{\text{eff}}$ to properties of the CE system is needed.

Some observations of what are assumed to be progeny of CEs have resulted in
estimates of $\tilde{\alpha}_{\text{eff}}$ with large uncertainties. Over 50 such systems (white dwarf-main sequence binaries) are identified and studied by Zorotovic et al. (2010) who concluded that these systems have ejection efficiencies that are consistent with $\tilde{\alpha}_{\text{eff}} \simeq 0.2 - 0.3$. Cojocaru et al. (2017) agree generally, though through population synthesis studies of Galactic white dwarf main-sequence binary data from the Sloan Digital Sky Survey (SDSS) Data Release 12. In a different population synthesis study, $\tilde{\alpha}_{\text{eff}} > 0.1$ reasonably described the ejection efficiency of late-type secondary binary systems while also producing post-CE systems with an overabundance of $> 1$-day orbital periods than is observed (Davis et al., 2010). Toonen and Nelemans (2013) argue that in order to produce these sub-day periods, the ejection efficiency must be low.

The relationship between the mass ratio of the binary, $q = m_2/M_1$, and the ejection efficiency has been studied by multiple authors but no consensus has been reached. A study by De Marco et al. (2011) reveals an anti-correlation between $q$ and $\tilde{\alpha}_{\text{eff}}$ while a study by Zorotovic et al. (2011) finds the opposite. In the former work, it is argued that larger companion masses result in lower ejection efficiencies, while in the latter the larger initial orbital energy of the companion mass is shown to increase the ejection efficiency. These conflicting results are compared to those found in this work in Section 4.

Multiple groups have also studied common envelope systems via three-dimensional hydrodynamic simulations (Ricker and Taam, 2012; Passy et al., 2012; Ohlmann et al., 2016; Chamandy et al., 2018a). In these simulations, the envelope of the CE begins to move outward but remains bound, thus failing to eject the CE. Proposed solutions to this unbound envelope problem involve additional energy sources like recombination energy, accretion, and jets, long-timescale processes, or dust-driven winds (Soker, 2015; Ivanova et al., 2015; Kuruwita et al., 2016; Glanz and Perets, 2018; Sabach et al., 2017; Grichener et al., 2018; Kashi and Soker, 2018; Ivanova, 2018; Soker et al., 2018). These
effects may eventually prove necessary but the physics included in (or excluded from) simulations should first be scrutinized.

Radiation allows the energy from the inspiraling companion body to be lost from the system. Without radiation, the energy should transfer into the primary and remain there in some form. For this reason, it is important to note that the aforementioned simulations exclude radiation from the system as a form of energy loss, thus painting an incomplete picture of the ejection efficiency. The energy budget and energy loss mechanisms in CE simulations should be examined and a discussion of the reasons behind the envelope remaining bound are necessary (e.g. Chamandy et al. (2018b)).

One energy source that has been examined in combination with convection in CE systems is recombination. In a system where the companion deposits energy into the envelope, the envelope expands and the convection provides an efficient transport mechanism to move the energy to the surface regions where it is radiated away and lost in a work by Grichener et al. (2018). Another work finds that energy transport via convection cannot be neglected in the case of helium recombination (Sabach et al., 2017). Recombination arguments and whether they can drive envelope ejection is currently under debate (Ivanova, 2018; Soker et al., 2018).

2 Methodology

To analyze the interactions of stars in common envelope systems, the primary star and its interior structure must be modeled. The models for this work were produced using an open-source stellar evolution code, Modules for Experiments in Stellar Astrophysics, or MESA (release 10108) (Paxton et al., 2011, 2018). MESA allows users to tune specific parameters in pre-made modules and produce spherically symmetric models of a star’s interior at discrete times in its evolution. For stars in the mass range
0.8\(M_\odot\) – 6.0\(M_\odot\), in increments of 0.2\(M_\odot\), the 1M\texttt{pre}\_\texttt{MS\_to\_WD} module was modified and run to completion, to avoid biases in the selection of maximum radius, described later. A full stellar evolution of a 1.4\(M_\odot\) star as produced by \texttt{MESA} is shown in Figure 4. The lower bound of 0.8\(M_\odot\) marks the minimum mass star that has evolved off of the main sequence during the universe’s lifetime.

![Figure 4: The radial evolution of a 1.4\(M_\odot\) \texttt{MESA} modeled star is shown.](image-url)
Modifications to the pre-written **MESA** module were minimal. Initial mass was incremented with each completed run. The allowed spacing of profile outputs was reduced for a finer time resolution. Mass-loss prescriptions remained as the default: the **MESA** modules used Reimer’s mass loss on the Red Giant Branch (RGB) and Blöcker’s mass loss for the Asymptotic Giant Branch (AGB). These prescriptions are

\[
\dot{M}_{\text{Reimers}} = 4 \times 10^{-13} \eta_R \frac{LR}{M}
\]

and

\[
\dot{M}_{\text{Blöcker}} = \eta_B \dot{M}_{\text{Reimers}},
\]

respectively (Reimers, 1975; Bloeker, 1995). The \( \eta \) values in the **MESA** modules were kept at \( \eta_R = 0.7 \) and \( \eta_B = 0.7 \). All stellar models were evolved assuming solar metallicity \( (z = 0.02) \).

The **MESA** modules produce profiles detailing the interior structure of the star at times all throughout the star’s evolution. For this work, the maximum radius profile of each stellar model, or the appropriate peak of the AGB or RGB, was extracted and used for common envelope interaction analysis. The time of maximum radius of a primary star is the time at which engulfment of the companion body is most likely, as it corresponds to the time of its maximum volume, when tidal torques that shrink the companion’s orbit will be strongest (Villaver and Livio, 2009; Nordhaus et al., 2010; Nordhaus and Spiegel, 2013). This age is also appropriate for study as any companion within the range of engulfment will have been engulfed by this time.

The interior of the star is modeled for each time-step, but due to computing constraints, only one of 20 interior profiles was stored, thus defining the time resolution of the model. This resolution was decreased from the default 50, with the exception of the few high-resolution cases necessary for examples later which were decreased from 50 to
5. Because of this, the maximum radius profile used for analysis is within 10 timesteps of the exact maximum radius. All profiles used were within 3% of the actual maximum radius, with one exception, which deviated 6%. (In fact, only 7 of 27 deviated more than 0.4% from the true maximum radius.) From this maximum radius profile, radial data on the primary’s mass, density, convective properties, and core/envelope boundaries are extracted. As an example, the density and enclosed mass of the 1.4$M_\odot$ model from Figure 4 are shown in Figure 5. These interior structure data are then used to compute, at each radius, the primary’s binding energy and the convective timescales (which define the convective zones). With radial information about the primary star’s interior, properties of the companion mass can also be calculated, e.g. the tidal disruption radius, the inspiral timescale, and the energy released during orbital decay. All of these parameters are discussed in detail below.

![Figure 5](image)

Figure 5: The radial density and enclosed mass of a 1.4$M_\odot$ MESA modeled star are shown.

### 2.1 Determining Convective Regions

Since each primary star in this study is a post-main sequence star, it is known that each hosts a deep convective region. The companion’s shrinking orbital radius during inspiral
releases orbital energy which is deposited into the region surrounding the companion’s mass. If this occurs within a near-surface convective region, convective eddies can carry energy to optically thin, exterior regions of the primary star where it can be radiated away. Due to the radiation of the energy, the companion’s released orbital energy cannot accumulate to eject the envelope of the primary star until much deeper into the inspiral, in many cases. To determine where in the primary star convective transport dominates, the convective regions must be identified.

The convective velocities are computed by MESA and used to determine the convective timescales of the primary star at each radius, via:

\[ t_{\text{conv}}[r] = \int_r^{R_\ast} \frac{1}{v_{\text{conv}}} \, dr. \]  \hfill (3)

The time it takes for a companion to fully inspiral through the star can also be calculated, again using properties from the MESA profile. The inspiral timescale is:

\[ t_{\text{inspiral}}[r] = \int_{r_i}^{r_{\text{shred}}} \frac{\left( \frac{dM}{dr} - \frac{M[r]}{r} \right)}{4\xi \pi G m_2 r \rho[r]} \sqrt{v_r^2 + \bar{v}_d^2} \, dr, \]  \hfill (4)

and has been derived from Eq. 9 in Nordhaus and Blackman (2006). Here, \( r_i \) is the initial radial position of the companion that the energy transferred is not in an optically thin region of the envelope. The tidal shredding radius, or the radius at which the companion tidally disrupts is estimated as \( r_{\text{shred}} \sim R_2 \sqrt{2M_{\text{core}}/m_2} \) and for slow rotators such as those RGB/AGB stars in this study, \( \bar{v}_d = v_\phi - v_{\text{env}} \simeq v_\phi \) (Nordhaus et al., 2007). We assume a value of \( \xi = 4 \), where \( \xi \) accounts for the wake produced by the inspiraling companion, the gaseous drag of the envelope, and the Mach number (Park and Bogdanović, 2017). For the companion-primary mass ratios included in this work, the ejection efficiency, \( \bar{\alpha}_{\text{eff}} \), is not sensitive to changes in \( \xi \).
Having determined the inspiral and convective timescales, two distinct regions arise: where $t_{\text{conv}} > t_{\text{inspiral}}$, and where $t_{\text{conv}} < t_{\text{inspiral}}$. For stars with mass $\gtrsim 4.0M_\odot$ a third region exists, where $t_{\text{conv}} < t_{\text{inspiral}}$, but in a physically distinct secondary layer which does not reach the surface of the primary. In regions where $t_{\text{conv}} \ll t_{\text{inspiral}}$, the convective eddies can carry the released orbital energy of the inspiraling companion toward the surface of the primary where it will be radiated away. We name this region the surface-contact convective region, or SCCR.

In Figure 6, the inspiral and convective timescales for companion masses ranging from $0.002 - 0.5M_\odot$ and primary masses from $1.0 - 6.0M_\odot$, respectively, are shown. The SCCR for each primary is shaded yellow, and the secondary convective regions are shaded pink. Though the entire radius range is shaded, it is important to note that convection only dominates in cases where the inspiral timescale is greater than the convective timescale. The shredding radius of each companion is marked with an X. The depth of the SCCR and the comparative timescales are especially important, and an analysis of the SCCR is performed throughout this work.

### 2.2 Energy and Luminosity Considerations

#### 2.2.1 Energy Conservation

The energy required to expel the primary’s envelope is called the binding energy and must first be found in order to compute the ejection efficiency. The minimum binding energy required to strip the envelope exterior to a radius, $r$, is:

$$E_{\text{bind}}[r] = - \int_M^{M_\odot} \frac{GM[r]}{r} dm[r],$$

where $M_\odot$ is the total mass of the star. Some studies employ a “$\lambda$-formalism,” which is used to approximate the binding energy of the star in observational cases where
Figure 6: Comparative timescale plots for a sample of representative primary masses at their maximum radial extent and several test companion masses. The convective timescale profile of the primary star is shown in solid blue. The colored, dashed lines show the inspiral timescale - the time it takes for the companion mass to spiral from its current radius to the center of the primary star. The radius at which each companion mass shreds due to the gravity of the primary mass is marked with an X. The surface-contact convective regions (SCCRs) of the primary star that do not contribute to the unbinding of the envelope are shaded in yellow. Interior convective zones that do not extend to the primary’s surface are shaded in pink.
the specific internal structure cannot be determined (De Marco et al., 2011). Since\textsc{MESA} models are used and have detailed interior structure profiles, no $\lambda$ approximations are necessary. The internal energy of each shell is excluded from the binding energy calculation since its effect on the binding energy has not been shown to be significant (Han et al., 1995; Ivanova et al., 2013).
As the companion contacts the surface of the primary star, the envelope’s mass will slow the radial velocity of the companion in orbit. This in turn shrinks the orbit, thus releasing orbital energy into the envelope. The released energy can be calculated as:

\[ \Delta E_{\text{orb}}[r] = \frac{G m_2}{2} \left( \frac{M[r_1]}{r_1} - \frac{M[r]}{r} \right), \]  

where \( r_1 \) is the orbital radius of the companion when energy is first released and \( m_2 \) is the mass of the companion.

Since the energy of the system is being passed from the companion to the primary, Equations 5 and 6 can be equated with an efficiency factor, \( \alpha_{\text{eff}} \) via:

\[ E_{\text{bind}} = \alpha_{\text{eff}} \Delta E_{\text{orb}}. \]  

Here, \( \alpha_{\text{eff}} \) represents the efficiency of energy transfer into unbinding the envelope from the decaying orbit of the companion. For 100% efficient transfer, \( \alpha_{\text{eff}} = 1 \), and all of the released orbital energy can be used to eject the envelope (ejection is, however, not guaranteed, as the orbital energy released must exceed that of the binding energy). In contrast, for fully inefficient transfer, \( \alpha_{\text{eff}} = 0 \) and no orbital energy contributes to ejecting the envelope, leaving the envelope bound. The efficiency \( \alpha_{\text{eff}} \) is discussed in the context of the SCCRs in Section 3.

### 2.2.2 Luminosity Requirements

The convective envelope of the primary can transport a limited amount of power before the convection becomes supersonic. Supersonic convection requires a more rigorous treatment than is allowed by MLT. This maximum luminosity is given by:

\[ L_{\text{max,conv}} = \beta 4\pi \rho[r] r^2 c_s^3[r], \]  

where \( \beta \) is a constant.
Figure 7: The maximum luminosity carried by convection, $L_{\text{max, conv}}$ for two primary masses in thick green curves, is shown with the drag luminosity of several companions for the two primary mass cases in dashed, colored lines. The tidal disruption radii are marked with an X for the 1.0$M_\odot$ case and a triangle for the 6.0$M_\odot$ case. This demonstrates that convection can carry the liberated orbital energy to the surface where it is radiated away.
where $\beta \approx 5$ (Grichener et al., 2018). The primary’s density profile ($\rho[r]$) and sound speed profile ($c_s[r]$) are taken directly from the MESA models. As the companion plunges through the envelope, it generates additional luminosity. This drag luminosity can be found via:

$$L_{\text{drag}} = \xi \pi r_{\text{acc}}^2 \rho[r] v_\phi^3[r]$$

(9)

where $r_{\text{acc}}$, the accretion radius, is given by:

$$r_{\text{acc}} = \frac{2Gm_2}{v_\phi^2[r]}$$

(Nordhaus and Blackman, 2006). If the drag luminosity does not exceed the maximum transportable luminosity, then convection can successfully carry it away.

The condition $L_{\text{drag}} \leq L_{\text{max,conv}}$ is met for all mass ratios in this work. This is presented in Figure 7. The maximum transportable luminosity for the $1.0M_\odot$ and $6.0M_\odot$ primary masses are shown in bold, solid and dotted green curves, respectively.

### 2.3 Outcomes of Common Envelope Interactions

Common envelope interactions can ultimately end in one of two outcomes: the companion ejects the envelope and survives to be in orbit around a white-dwarf core, or the companion tidally shreds before it transfers enough energy to eject the envelope. Whether or not the companion survives is largely dependent on its radius, a proxy for density. The companion’s radius can be estimated based on its mass. The companion masses in this study encompass three different mass ranges: planet-mass ($m_2 \leq 0.0026M_\odot$, Zapolsky and Salpeter 1969), brown dwarfs ($0.0026M_\odot < m_2 < 0.077M_\odot$, Burrows et al. 1993), and stellar mass ($m_2 \geq 0.077M_\odot$) objects. For planet-mass objects, the radius is approximated to be $R_{\text{Jupiter}}$. From Reyes-Ruiz and Lopez (1999), the radius for brown
dwarfs is:

\[
R_2/R_\odot = 0.117 - 0.054 \log^2 \left( \frac{m_2}{0.0026 M_\odot} \right) + 0.024 \log^3 \left( \frac{m_2}{0.0026 M_\odot} \right)
\]

and for stellar-mass main-sequence companions is:

\[
R_2 = \left( \frac{m_2}{M_\odot} \right)^{0.92} R_\odot.
\]

If there is an orbital separation, \(a\), where: (i.) \(\alpha_{\text{eff}} \Delta E_{\text{orb}}[a] > E_{\text{bind}}[a]\) and (ii.) \(a > r_{\text{shred}}\), then the common envelope interaction can end in a short-period binary. The shredding radius is calculated as described in Section 2.1. In Figures 6 and 8, the shredding radii of each companion are marked with an X. As the companion inspirals, it releases energy with the decreasing orbital radius. For companions which tidally disrupt closer to the primary’s core, the change in orbital energy, and thus the energy that can contribute to unbinding the envelope, is greater than for those companions which disrupt closer to the surface. The energy that can contribute to unbinding the envelope will be maximized if the companion’s shredding radius is deeper than the lower boundary of the SCCR. The convection within the SCCR aids in reducing the energy available for unbinding the envelope, as it carries the energy to the surface to be radiated away. This is discussed further in Section 3.

### 3 Ejection Efficiency in Convective Regions

The ejection efficiency, \(\alpha_{\text{eff}}\), of a CE interaction is composed of a weighted average of positionally dependent energy transfer efficiencies. The energy transfer efficiency, \(\alpha_{\text{eff}}\), can be found at each radius of inspiral using analysis of the \texttt{MESA} profiles in the
Figure 8: Comparative energy plots for a sample of representative primary masses at their maximum radial extent and several test companion masses. The binding energy for the primary star is shown in solid blue. The colored, dashed lines show the change in orbital energy of the companion star as it inspirals, and the radius at which the companion shreds is marked with an X. (Several X’s in the 3.0$M_\odot$ plot fall below $10^{44}$ erg.) In cases where the X falls below the binding energy curve, the companion will disrupt during inspiral before enough energy is transferred to unbind the envelope of the primary. These orbital energy curves take into account the convective zones of the primary, in that movement through the surface-contact convective regions (SCCRs) does not contribute energy to the ejecting of the envelope.
following way. If the companion is orbiting in a region where \( t_{\text{conv}} < t_{\text{inspiral}} \) which is within the SCCR, the released orbital energy is carried by convective transport to an optically thin region where it is radiated away from the system. For this reason, regions within the SCCR are assigned \( \alpha_{\text{eff}} = 0 \), as the energy transfer in these regions can be considered perfectly inefficient. In contrast, if the companion is orbiting in a region where \( t_{\text{conv}} > t_{\text{inspiral}} \), the released orbital energy remains within the system and all the energy released at that radius contributes to unbinding the envelope. In addition, regions that are considered convective but do not contact the surface of the primary can aid in mixing the released orbital energy, but cannot radiate it away, thus leaving the energy to contribute to envelope ejection. These regions are assigned \( \alpha_{\text{eff}} = 1 \), as the energy transfer therein is considered perfectly efficient. The \( \alpha_{\text{eff}} \) values are summarized mathematically:

\[
\alpha_{\text{eff}}[r] = \begin{cases} 
0 & t_{\text{conv}}[r] < t_{\text{inspiral}}[r] \\
1 & t_{\text{conv}}[r] > t_{\text{inspiral}}[r].
\end{cases}
\]

To construct an average ejection efficiency of the system, a new prescription for the calculation of \( \bar{\alpha}_{\text{eff}} \) is derived for use if properties of the convective zones are known. To do so, we first determine the \( \alpha_{\text{eff}} \) values at each radius within the primary, calculate the released orbital energy at each radius, and integrate from the surface to the final radial position of the companion \( (r_f) \) via:

\[
\bar{\alpha}_{\text{eff}} = \frac{\int_{r_0}^{r_f} \alpha_{\text{eff}}[r] dE_{\text{orb}}[r]}{E_{\text{orb}}[r_f] - E_{\text{orb}}[r_0]};
\]

where \( r_f \) can take on one of two quantities:

\[
r_f = \begin{cases} 
 r_{\text{Ebind}} = \alpha_{\text{eff}}[r] \Delta E_{\text{orb}}, & r_{\text{Ebind}} = \alpha_{\text{eff}}[r] \Delta E_{\text{orb}} > r_{\text{shred}} \\
r_{\text{shred}}, & r_{\text{shred}} > r_{\text{Ebind}} = \alpha_{\text{eff}}[r] \Delta E_{\text{orb}}.
\end{cases}
\]
which represents the radius at which the energy transfer from the companion halts. If the companion shreds before ejecting the envelope, the coherent transfer of energy from inspiral can no longer occur. In a similar way, once the binding energy of the primary has been exceeded by the energy transferred from the inspiraling companion, the energy transfer ceases. The larger of these two quantities is taken as the final radial position of the companion, as the companion moves from the radius (larger radii) to the core.

Here, a discrete calculation of $dE_{\text{orb}}[r]$ can be done as in Equation 6. We assume a constant internal structure for the primary while the companion inspirals, and that released orbital energy is distributed to the local mass-shell.

Binding energy and change in orbital energies are shown in Figure 8. The binding energies are shown for primaries between $1.0 - 6.0 M_\odot$ in the thick blue lines. Overplotted are colored, dashed curves showing the change in orbital energy for companions with masses between $0.002 - 0.2 M_\odot$. Released orbital energy does not begin to accumulate and contribute to unbinding the envelope until the companion has inspiraled beyond the SCCR. The tidal shredding radius is marked with an X, at which point energy transfer stops.

The subplots of Figure 8 illustrate whether the companion successfully unbinds the envelope. For cases in which the companion shreds after exceeding the binding energy requirement, (i.e., the X falls above the $E_{\text{bind}}$ curve), the companion ejects the envelope down to the intersection of its $\Delta E_{\text{orb}}$ curve and the $E_{\text{bind}}$ curve. In many cases, this leaves a short-period binary. For a typical SCCR depth of $10^{11}$ cm (see Figure 6), companions between $0.008 - 0.02 M_\odot$ will survive the interaction, eject the envelope, and leave the system in a binary.

The curves’ intersection also estimates the final orbit of the system. Only when the binding energy is exceeded can the envelope of the primary be ejected. At this radius of energy equivalence ($r_{E_{\text{bind}}=\alpha_{\text{eff}}[r]\Delta E_{\text{orb}}}$), the energy liberated by the companion’s
decaying orbit can finally be deposited into the envelope rather than radiated away. This abrupt injection of energy into the system ejects the envelope and leaves the companion at that distance away from the center of the primary. For this reason, the radius at which the binding energy and orbital energy curves intersect in the panels of Figure 8 describes the final orbital separation of the binary.

3.1 Variability of the SCCR

We argue that the orbital energy that is liberated from the inspiraling companion is mixed within convective regions, and put emphasis on the ability for the SCCR to transport energy to optically thin areas to be radiated away, as presented in Section 2.1. It is therefore essential to evaluate the variability of the SCCR with time and primary mass, as it directly affects the ejection efficiency. Figure 9 shows differences in the SCCR with each primary mass, and the range of SCCR depths over time for each over the final thermal pulse of the primary (boxes and whiskers). The median convective depths are shown in orange and the SCCR depths at the time of maximum radius, the most likely time for a companion to be engulfed, are shown in purple.

If the SCCR were entirely stable, the boxplot would show no variation. Instead, variation can be seen both over time and by primary mass. The SCCR depths span a wide range for all primary masses \( \geq 1.4M_\odot \). For primaries \( \geq 3.2M_\odot \), the SCCR at the time of maximum radius is at the minimum convective depth. This arrangement maximizes \( \bar{\alpha}_{\text{eff}} \), as the companion travels furthest within the primary and can successfully inject energy into the envelope without it being convectively transported to the surface to be radiated. Conversely, if at maximum radius the SCCR is maximally deep, the companion may shred within the SCCR or shortly after emerging from it, which will minimize \( \bar{\alpha}_{\text{eff}} \), as most or all of the released orbital energy leaves the system.

Since the depth of the SCCR at the time of most likely engulfment (i.e. primary’s
maximum radius) is inconsistent, as seen in Figure 9, the SCCR depth over time is examined. Three models representative of a stable SCCR, maximum-SCCR-depth-at-
$r_{\text{max}}$, and minimum-SCCR-depth-at-$r_{\text{max}}$ are shown in Figure 10 with a $1.0M_{\odot}$ primary, $1.8M_{\odot}$ primary, and $4.6M_{\odot}$ primary, respectively. The radii over the final thermal pulse are shown in blue dashed curves and the SCCR depth is shown in colored, identically dashed curves. Since the ages of the primary stars and the time of maximum radius vary, the time on the x-axis is normalized to the maximum age of the star, and then centered around the time of maximum radius. In this way, $t = 0$ is the time of maximum radius for each primary. The ticks of lookback time can be estimated to be on the order of $\sim 10^2$ years. We note that $t > 0$ SCCR depths are shown for completeness, but are not analyzed in this work.

The stable SCCR model (the $1.0M_{\odot}$ primary) shows a nearly constant convective depth and constant radius with lookback time, while the minimum-SCCR-depth-at-$r_{\text{max}}$ ($4.6M_{\odot}$) model shows a slowly increasing SCCR depth and constant radius with time. Quite contrastingly, the maximum-SCCR-depth-at-$r_{\text{max}}$ ($1.8M_{\odot}$) model shows a correlated radius and SCCR depth fluctuation just prior to $r_{\text{max}}$. This deep SCCR minimizes $\bar{\alpha}_{\text{eff}}$, and shows that knowledge of the depth of the SCCR, and thus the time of engulfment, is imperative to an understanding of the ejection efficiency of the system.
Figure 9: Box-and-whisker plot shows the range of convective depths during the final thermal pulse of the primary mass just prior to and including the time of maximum radius (does not include any time after the maximum radius). The orange line inside the box shows the median value of the boxplot, the vertical extent of the box marks the interquartile range (IQR: the middle 50% of the range), and the upper and lower bounds of the whiskers mark the minimum and maximum convective depths, respectively. Note that for primary masses below 1.4$M_\odot$ the spanned range is very small, showing a stable convective region.
3.2 Ejection Efficiency, $\bar{\alpha}_{\text{eff}}$

The internal stellar structure of the primary and the properties of the companion uniquely determine the ejection efficiency for each primary-companion mass pair. We present $\bar{\alpha}_{\text{eff}}$ values for a matrix of primary-companion pairs in Figure 11, calculated as described in Equation 11. Note that the range of companion masses here exceeds that of earlier analyses for completeness.

The horizontal stripes between $1.2M_\odot$ and $3.0M_\odot$ are a result of the variability of the SCCR, as described in Section 3.1. Due to the depth of the SCCR in these cases (see e.g. $3.0M_\odot$ panel of Figure 6), most companion masses included in the colormap inspiral on timescales less than the convective timescale, therefore efficiently transferring the liberated orbital energy to the envelope and maximizing $\bar{\alpha}_{\text{eff}}$.

Primary masses $> 3.0M_\odot$ show consistently low $\bar{\alpha}_{\text{eff}}$ values. Unlike the deep SCCR of the $3.0M_\odot$ model, the lower bound of the SCCR is approximately $10^{11}$ cm, and the additional shell mass from the increased primary star mass increases the inspiral timescale of the companion. This combination allows for energy to be radiated from optically thin areas via convective transport, thus lowering $\bar{\alpha}_{\text{eff}}$ values. If the SCCR were stable in the lower mass ranges, we would expect a smooth spread of $\bar{\alpha}_{\text{eff}}$ values, though higher than those presented $> 3.0M_\odot$.

The trends seen in the colormap make obvious the strong dependence of $\bar{\alpha}_{\text{eff}}$ on the depth of the SCCR, which can be highly variable with time (see Figure 10). For this reason, we argue that the ejection efficiency of common envelope interactions is sensitive to the age of the primary when the CE phase occurs.
Figure 10: The SCCR depths over time are shown along with the primary’s radius for three representative primary masses. The x-axis is a lookback time until maximum radius, described by: \( \frac{t \left[ r_{\text{max}} \right]}{t \left[ r \right]} \). The vertical black line marks the time of \( r_{\text{max}}, t = 0 \). (Times after maximum radius are shown here for completeness but are not examined in this work.) The blue lines show the fraction of maximum radius in time. Two of the three blue lines overlap at unity. The colored, dashed lines show the SCCR depth over time. Note the instability in the convective zone as it approaches the maximum radius for the 1.8\( M_\odot \) model. (Convective depth is maximized with decreased interior convective radius.)
4 Discussion

The ejection efficiencies found from the simulated MESA data vs. $\log(m_2/M_1)$ are compared to those found observationally by De Marco et al. (2011) and Zorotovic et al. (2011). Our $\bar{\alpha}_{\text{eff}}$ values are shown in Figure 12, first constrained to the parameter space presented by De Marco et al., and then unconstrained. The mass ratios considered in this work do not exceed $q = 0.5$ ($\log(q) \simeq -0.3$). Note that the colorbar in Figure 12 shows the range of primary masses studied, unlike Figure 11, which shows the range of
ejection efficiencies.

In the axis-constrained plot (top), there is an evident anti-correlation of $\bar{\alpha}_{\text{eff}}$ with mass ratio, but each with different slopes. This is in agreement with De Marco et al.’s findings of an anti-correlation within this parameter space. In contrast, Zorotovic et al. find lower companion masses result in larger final separations. In the full parameter space, we too see some regions where $\bar{\alpha}_{\text{eff}}$ positively correlates with mass ratio.

Both De Marco et al. and Zorotovic et al. use the $\lambda$-formalism to estimate $\bar{\alpha}_{\text{eff}}$, since they both use observations of systems that are assumed to be progenitors of CEs, which can result in ejection efficiencies that are greater than unity. Since we use MESA models which provide detailed interior structure profiles, a direct comparison in $\bar{\alpha}_{\text{eff}}$ values is difficult.

In this work, we find that the ejection efficiency is sensitive to the convective structure of the primary during inspiral. This is in agreement with Politano and Weiler (2007), who argue that the ejection efficiency is dependent on the interior structure of the primary and the companion mass. Ultimately, we find that mixing within the convective regions of the evolved primary is essential to determining the $\bar{\alpha}_{\text{eff}}$ value.

As described in Section 2.1, the convective regions can aid in mixing in different ways, depending on their location. During the CE phase, the companion’s liberated orbital energy can be carried away from the body of the companion and distributed into other regions of the primary. Convection within the SCCR allows energy to be transported to an optically thin surface where it is radiated out of the system. For this work, we assume at all of the companion’s released orbital energy that is released within the SCCR is distributed among the local mass-shell and successfully leaves the system as radiation, thus providing a lower limit on the system’s ejection efficiency.
Figure 12: Top: Axis-constrained mass ratio and corresponding $\bar{\alpha}_{\text{eff}}$. These axis limits are comparable to the parameter space examined by De Marco et al. (2011), who also found a negative slope in this range. Bottom: Mass ratio and $\bar{\alpha}_{\text{eff}}$ for all primary-companion mass pairs in this study.
Following the assumption of constant interior structure during the CE evolution, the interior structure at the maximum radius of the star during its evolution is used to examine the ejection efficiency of the system. This is the point in the binary’s evolution when the companion is most likely to be engulfed. We assume that the companion begins to skim the surface of the primary when it is fully extended. In some cases, we find that the SCCR depth can vary drastically in as quickly as $\sim 10^2$ years. The length of the entire CE phase is estimated to be of similar length. The $\bar{\alpha}_{\text{eff}}$ values presented here, however, assume a constant internal primary structure during the CE phase. For this reason, the true ejection efficiencies may vary some, as the primary’s interior may change for a number of reasons. First, though the CE phase of the entire evolution of the system is only a small fraction of time, the primary may continue to evolve after the companion has been engulfed. Second, disturbances from the companion’s mass or wake during inspiral have the potential to affect the primary’s interior. As such, it is important to note that the $\bar{\alpha}_{\text{eff}}$ presented in Figure 11 values cannot be generalized. Instead, the employment of Equation 11 with knowledge of properties of the SCCR at the exact time of engulfment can better determine the ejection efficiency of the system.

4.1 Implications of Convection

Radiation of orbital energy through convective transport allows the binary system to close into a short-period binary. In many of the primary-companion pairs, these close orbits have periods of less than a day. This finding may well be a solution to the current underrepresentation of such sub-day period systems in population synthesis studies (Davis et al., 2010). Incorporating Equation 11 into CE progeny population studies could yield interesting results with an advanced understanding of the ages of the systems, including the primaries, at the time of the companion’s engulfment.
The stable SCCR\textsubscript{s} in the higher mass primaries (\(\geq 4.0M_\odot\)) in combination with the companion masses that survive and unbind the envelope yield sub-day periods. The companions which do not survive the interaction long enough to eject the envelope cannot yield any compact binary system. The companions with short inspiral timescales, like many of those shown in the 1.0 – 3.0\(M_\odot\) panels of Figure 6, are less affected by convective transport as the speed of the inspiral dominates over the speed of the convective eddies. In these cases, the final separation of the larger companion bodies yields \(\sim\)3-day periods. The smaller companion bodies which survive continue to yield \(\lesssim\) 1-day periods. The final separations can be estimated by the intersection of the energy curves in Figure 8.

In some numerical simulations, gas within the star reaches co-rotation and slows the rate of orbital decay, thus increasing the inspiral timescale (Ricker and Taam, 2012; Ohlmann et al., 2016; Chamandy et al., 2018a). While co-rotation cannot be perfectly sustained within a turbulent medium, its potential to increase the inspiral timescale (lead to faster decay times) has interesting implications. We note that as long as the orbital decay timescale is larger than the convective timescale in the SCCR, energy transfer to the surface will continue to dominate.

We have neglected some effects that many increase the inspiral timescale, thus increasing the effect of convection on CE systems. The gas is assumed to have no velocity during inspiral and therefore cannot spin-up and approach co-rotation with the orbit, which has been found in some numerical simulations. If, instead, the gas reaches co-rotation, then the inspiral timescale will be greater than is presented above. In that case, our lowest-mass primaries which do not effectively transport convection in the configurations presented here would in fact allow convection to dominate and carry the energy to the surface to be radiated away. Similarly, we have assumed that the convective properties remain constant despite the companion moving through the envelope. The transfer of energy from the companion to the convective regions could
result in higher convective velocities, thus shortening (increasing the effect of) convective transport timescales. Therefore, these results are conservative and the incorporation of both effects is an interesting future direction.

As described in Section 2.1, we assume that if the convective transport dominates, 100% of the released orbital energy is contributes to unbinding the envelope and $\alpha_{\text{eff}}[r] = 1$. This means that we also assume that the energy gets redistributed equally to the local mass-shell. At the lower bound of the SCCR, the mixing may, in fact, distribute the energy well enough to eject the entire envelope. Mixing within the secondary convective zones that are present in primaries of mass $\geq 3.0M_\odot$ may mix the energy of the inspiraling companion as well. Distribution and mixing of released orbital energy are topics of active study by numerical simulations (see Chamandy et al. 2018b for more discussion).

5 Conclusions and future directions

Finding the ejection efficiency of common envelope interactions is a topic of active research. In this work, we study how convection affects these ejection efficiencies, or $\bar{\alpha}_{\text{eff}}$. To do so, the $\bar{\alpha}_{\text{eff}}$ values were calculated for a matrix of primary-companion mass pairs with convective mixing taken into account. The surface-contact convective regions (SCCRs) of the primary stars highly affect the ejection efficiencies of the system, as the convective timescales dominate over many of the inspiral timescales of the companions. Within these convective regions, the released energy due to the orbital decay of the companion can be carried to an optically thin surface to be radiated away. This lowers the ejection efficiency since less of the energy remains in the system.

When convection is considered, the orbital radii shrink to $10^{11}$ cm in many cases, and may in more cases with the inclusion of co-rotation. This could be a solution to the
underrepresentation of short-period binaries in population synthesis studies, which use universal ejection efficiencies, without requiring additional energy sources. Since energy released within the SCCR is radiated away, the liberated orbital energy cannot begin to contribute to ejecting the envelope until deeper into the primary’s envelope.

A main contribution is the new $\dot{\alpha}_{\text{eff}}$ prescription as described in Equation 11. This calculation can be carried out if properties of the convective zones, especially the SCCR, are known. Since the SCCR depth changes over time, and the ejection efficiencies are sensitive to that depth, it follows that the ejection efficiency is dependent on the internal structure of the primary at the time of the CE, and thus the age of the primary. Regardless of the exact age of the primary, the inclusion of convection in mixing will consistently be important, since evolved giants host deep convective envelopes.

There are several directions toward which this work could point. Observational work could be done to study the relationship between core mass and post-CE orbital separations, then compare with those presented in this work. From this work, it is expected that since the inspiral times of the companions increase with increased primary mass, the convection affects companions more consistently with larger core masses. Therefore, the spread of post-CE orbital separations should change with primary core mass; the spread would be greater for lower core masses than more massive cores. This work may not be straightforward due to the time variability of the SCCR.

Theoretical work can continue as follows. First, an extension of this work would include co-rotation and a more detailed understanding of how it affects the inspiral timescale, and thus the ejection efficiency. Second, numerical work on high-resolution simulations of convection within the envelopes of giant stars should be performed. This may include incorporating convective energy transport in stratified wind tunnel studies (MacLeod et al., 2017). Third, the stars included in this work are relatively low-mass. A study of high-mass stars in common envelopes and the ejection efficiencies therein
could give context on compact-object mergers which may result on gravitational waves (Belczynski et al., 2016). Finally, dynamical calculations which find the time when the companion is engulfed, from which the age of the primary can be found, can be paired with findings from this work to build better prescriptions for ejection efficiencies. This would then be used to study stellar and common envelope populations (Belczynski et al., 2002; Moe and De Marco, 2006).
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