White Dwarfs as Probes of Fundamental Physics: Tracers of Planetary, Stellar and Galactic Evolution
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Convection in common envelopes and the formation of double white dwarfs

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Abstract. Formation of close double white dwarfs likely requires the initial binary system to evolve through two successive common envelope (CE) phases. A prominent method for describing CE outcomes involves defining an ejection efficiency, $\bar{\alpha}_{\rm eff}$, which quantifies the fraction of orbital energy available to unbind the envelope. Reproducing observed post-CE orbital parameters has proven difficult for numerical simulations, as the companion's decaying orbit fails to eject the envelope. The ejection failure seen in numerical simulations may be resolved with a proper treatment of convection, whereby the binary orbit shrinks before energy can drive ejection. Where the orbital decay timescale exceeds the convective transport timescale, the energy released during inspiral is carried to the stellar surface and radiated away. By including convection, we produce sub-day post-CE orbital periods, a result consistent with observations. We comment on the effects of convection for the population of double white dwarfs that evolve through two CEs.

Keywords. (stars:) binaries: general, stars: AGB and post-AGB, planet-star interactions – convection, (stars:) white dwarfs, (stars:) binaries: close

1. Introduction

The common envelope (CE) phase is believed to be the primary mechanism for producing short-period (sub-day) compact white dwarf (WD) binary systems (Toonen & Nelemans (2013); Canals *et al.* (2018)). As the more massive star in a binary system leaves the main sequence it begins to expand significantly during the Red Giant and Asymptotic Giant Branch phases (RGB and AGB). At this stage, the primary may reach the orbital radius of the companion star, overflow its Roche Lobe, or experience orbital decay through tidal dissipation (Nordhaus & Blackman (2006); Nordhaus *et al.* (2010); Chen *et al.* (2017)). In each of these scenarios, the companion can be engulfed in the outer layers of the primary star such that the primary's core and the companion orbit within a shared common envelope (Paczynski (1976); Ivanova *et al.* (2013); Kochanek *et al.* (2014)).

Orbital decay transfers energy and angular momentum from the orbit to the CE which can be tapped to eject the envelope which, if successful, results in a post-CE tight binary (Iben & Livio (1993)). Quantifying this process via energy arguments involves defining an ejection efficiency which describes what fraction of the companion's lost orbital energy can contribute to the unbinding of the envelope (Iben & Tutukov (1984); Webbink (1984); Livio & Soker (1988); DeMarco *et al.* (2011)). This is often parameterized by an α-prescription in the following way:

$$\bar{\alpha}_{\rm eff} = E_{\rm bind}/\Delta E_{\rm orb} \tag{1.1}$$

If the efficiency and energy of the inspiraling companion exceeds that of the binding energy of the primary star's layers, the envelope is ejected leaving behind a companion star in orbit around the primary's core, i.e. a star in orbit around a WD. Should this companion star now engulf the WD during its subsequent ascent up either the RGB or AGB, a second CE phase would ensue. After the envelope is ejected yet a second time, the system will end as a double white dwarf (DWD) whose orbit continues to decay via gravitational-wave radiation.

A giant star's envelope is almost fully convective, yet models of CEs completely neglect convection which can qualitatively change the outcomes. For example, convective eddies redistribute locally deposited energy globally. In addition, convective eddies can transport orbital energy to the surface of the CE where it can be lost via radiation, thereby lowering $\bar{\alpha}_{\rm eff}$ and bringing the two orbiting bodies closer together before the envelope is ejected (Wilson & Nordhaus (2019)). Below, we detail how including the effects of convection modify the outcomes of common envelopes.

2. Convective CE Model

During a CE, the companion plunges into a nearly-fully convective envelope of the primary star. In order to determine if the orbital energy of the companion contributes to unbinding the envelope, the convective transport timescale must be compared to the orbital decay timescale. The convective transport timescale is given by:

$$t_{\rm conv}[r] = \int_r^{R_*} \frac{1}{v_{\rm conv}[r]} dr \tag{2.1}$$

(Grichener, Sabach & Soker (2018)), and the time for the companion's orbit to decay is given by:

$$t_{\rm inspiral}[r] = \int_{r_{\rm i}}^{r_{\rm shred}} \frac{\left(\frac{{\rm d}M}{{\rm d}r} - \frac{M[r]}{r}\right)\sqrt{v_r^2 + \bar{v}_\phi^2}}{4\xi\pi G m_2 r \rho[r]} {\rm d}r, \tag{2.2}$$

where $r_{\rm shred}$ can be estimated as $r_{\rm shred} \sim R_2 \sqrt[3]{2M_{\rm core}/m_2}$. If the orbital decay timescale exceeds the convective transport timescale, the convective motion of the envelope's matter redistributes the energy deposited by the inspiraling companion and can carry the liberated energy to the surface of the star where it is radiated away from the system altogether. A representative timescale comparison plot can be seen in Figure 1. For higher-mass companions, the orbit decays more quickly, allowing those companions to feel the effects of convection for less of the duration of the common envelope phase.

The companion's released orbital energy is given by

$$\Delta E_{\rm orb}[r] = \frac{G m_2}{2}\left(\frac{M_{\rm i}}{r_{\rm i}} - \frac{M[r]}{r}\right). \tag{2.3}$$

This energy cannot contribute to unbinding the envelope until it reaches a region of the CE where the convective transport timescale is longer than the orbital decay timescale. This certainly occurs in non-convecting regions but can also occur in convecting layers. This allows the companion to inspiral deep into the star before orbital energy can be tapped to drive ejection. The radius within the primary at which the change in orbital energy exceeds the binding energy of the primary is the radius at which the envelope is unbound and ejected. A representative plot which shows the location where the binding energy is exceeded can be seen in Figure 2. With the envelope expelled from the system, a white dwarf with a short-period companion remains. By including convective effects, CE phases with M-dwarf companions result in sub-day orbital periods around WDs (Wilson & Nordhaus (2019)), consistent with observations (Davis *et al.* (2010)).

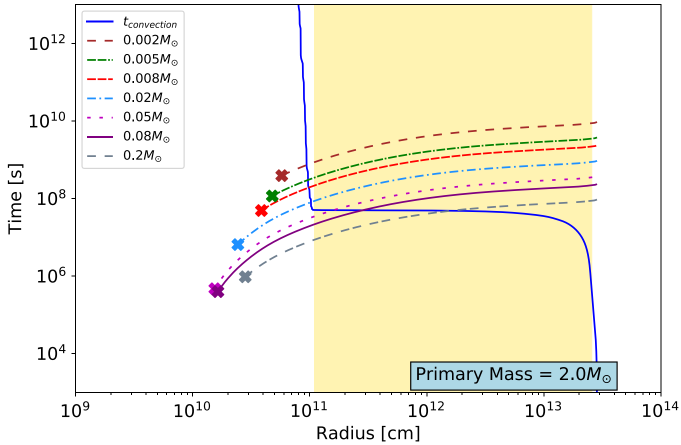

Figure 1. The convective transport timescale (solid curve) is compared to the orbital decay timescales of several companion masses (dashed curves). The shaded region that extends from $\sim 10^{11}$ cm to the surface of the star indicates the convective region of the primary star. Where the orbital decay timescale exceeds the convective transport timescale, the convective motion of matter within the primary's envelope redistributes the orbital energy released during inspiral. This energy can be carried to the surface where it is radiated away.

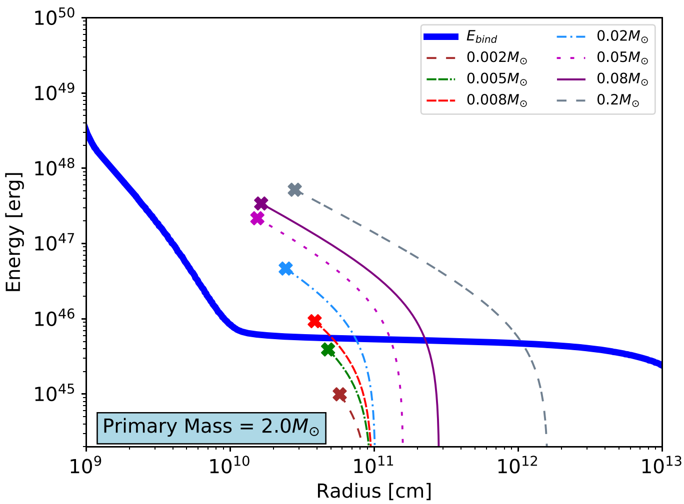

Figure 2. The binding energy (solid curve) of the primary is compared to the change in orbital energy of several companions (dashed curves). Energy released by the inspiraling companion only contributes to unbinding the envelope of the primary where the convective transport time exceeds the orbital decay time. The radius at which the change in orbital energy exceeds that of the binding energy is the radius at which the envelope is ejected. This results in M-dwarf+WD systems with short-period orbits ($\lesssim 1$ day).

3. Implications for Double White Dwarfs

The cessation of the first CE produces the initial conditions for the second phase which commences when the companion leaves the main-sequence. Since RGB/AGB stars possess rigorous convective envelopes, the effects of convection must also be incorporated in the second common envelope phase. Once again, the inspiraling white dwarf companion travels deep into the primary star before its energy can be tapped to eject the primary's

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extended envelope. With the employment of the convective $\bar{\alpha}_{\rm eff}$-prescription, DWDs in extremely short-period orbits are a common result following two successive CE phases.

The vast majority of observed DWD systems have orbital separations of less than 3×10^{11} cm, a result which can be quickly matched with a comparison of the depth the companion may travel before depositing its energy into the envelope. When the cores of primary stars have grown to the mass of observed WDs, the radius at the lower limit of the convective zone is also very frequently between 1×10^{11} and 4×10^{11} cm. This correlation has interesting implications for the formation and ultimate population of DWDs.

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