THE PAST AND FUTURE OF DETACHED DOUBLE WHITE DWARFS WITH HELIUM DONORS
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ABSTRACT

We present a method for modeling the evolution of detached double white dwarf (DWD) binaries hosting helium donors from the end of the common envelope (CE) phase to the onset of Roche Lobe overflow (RLOF). This is achieved by combining detailed stellar evolution calculations of extremely low mass (ELM) helium WDs possessing hydrogen envelopes with the orbital shrinking of the binary driven by gravitational radiation. We show that the consideration of hydrogen fusion in these systems is crucial, as a significant fraction (∼50%) of future donors are expected to still be burning when mass transfer commences. We apply our method to two detached eclipsing DWD systems, SDSS J0651+2844 and NLTT-11748, in order to demonstrate the effect that carbon-nitrogen-oxygen (CNO) flashes have on constraining the evolutionary history of such systems. We find that when CNO flashes are absent on the low mass WD (M₂ ≤ 0.18 M⊙), such as in NLTT-11748, we are able to self consistently solve for the donor conditions at CE detachment given a reliable cooling age from the massive WD companion. When CNO flashes occur (0.18 M⊙ ≤ M₂ ≤ 0.36 M⊙), such as in SDSS J0651+2844, the evolutionary history is eradicated and we are unable to comment on the detachment conditions. We find that for any donor mass our models are able to predict the conditions at reattachment and comment on the stabilizing effects of hydrogen envelopes. This method can be applied to a population of detached DWDs with measured donor radii and masses.

Subject headings: binaries: close— Galaxy: stellar content— stars: general— white dwarfs

1. INTRODUCTION

Detached DWD binaries are considered to be the progenitors of a variety of intriguing systems and explosive phenomena such as AM CVn stars, type Ia and possibly type II supernovae (Kilic et al. 2014a; Bildsten et al. 2007; Iben & Tutukov 1984; Webbink 1984; Guillochon et al. 2010; Pakmor et al. 2012). Recently, considerable effort has been put into studying the stability of these systems when they come into mass transfer, as those which become dynamically unstable and merge have emerged as a viable candidate for type Ia supernovae (referred to as DETONATORS) throughout much of the parameter space (Dan et al. 2012).

Systems which will come into contact within a Hubble time (referred to as merger systems) are the end products of a violent and hydrodynamically rich phase as they must have undergone one or two phases of unstable mass transfer driven by radius expansion during the giant phase (Marsh et al. 1995). During this phase, the ensuing single envelope embedding the two stars brings the system to smaller separations. The details of this CE phase are a subject of active investigation as they are difficult to constrain both observationally and theoretically (Ivanova et al. 2013). After the CE has ceased, retention of a small amount (10⁻³–10⁻² M⊙) of hydrogen on the donor will result in the ELM WD burning hydrogen in a thin shell and remaining bright for billions of years (Althaus et al. 2001; Serenelli et al. 2001; Panei et al. 2007).

As the systems are drawn closer together via gravitational radiation, they will eventually come into a phase of mass transfer. The system either merges or survives to become an interacting binary. For the system to survive the mass transfer rate must be stable, and this depends sensitively on the mass ratio (defined as q = M₂/M₁, where M₁ > M₂ is the accretor mass), angular momentum transport mechanisms and the donor’s internal structure (Marsh et al. 2004; Gokhale et al. 2007; Dan et al. 2011; Kremer et al. 2015).

The discovery of tens of detached DWD systems with ELM donors (M₂ ≲ 0.2 M⊙) has sparked an interest in the modeling of helium WDs with hydrogen envelopes, as their cooling ages depend on the details of the quiescent burning, the presence and effect of CNO induced thermonuclear flashes, and the insulating influence of their envelopes (Althaus et al. 2013; Istrate et al. 2014). Of these detached DWDs, 25 are merger systems, including 5 with merging times ≲ 100 Myr (Kilic et al. 2012, 2014b). We demonstrate in this Letter that during this pre-merger period we are able to make predictions about the thermal state of the donor at the beginning of RLOF, as well in some cases retrodictions about the conditions at the end of the difficult to constrain CE phase. We use two detached eclipsing DWD systems (SDSS J0651+2844 and NLTT-11748) as testbeds with a clear emphasis on the applicability of this method to others. In Section 2 we discuss the importance and prevalence of quiescent hydrogen burning. In Section 3 we present our method and apply it to determining the future and past evolution of SDSS J0651 and NLTT-11748. We discuss our results and conclude in Section 4.

2. THE ROLE AND UBiqUITY OF HYDROGEN IN DWDS

D’Antona et al. (2006) first explored the effect of hydrogen burning on an ELM WD donor at the onset of mass transfer with the aim of explaining the period decrease of the shortest orbital period binary, HM Cancri. The entropy injection due to the burning at the hydrogen/helium interface causes the WD radius to grow, reaching 10-100 times its zero temperature value depending on the amount of hydrogen in the envelope. As a result, the WD overflows its Roche lobe at larger separations. A key aspect is that the donor deviates from the standard WD mass-radius relation R₂ ∝ M₂¹/³ and it contracts as its hydrogen envelope is stripped. This has a two-fold effect: it reduces the equilibrium mass transfer rate and causes the period derivative to be dominated by gravitational wave losses as opposed to mass transfer. In this way, the presence of hydrogen serves to temporarily stabilize the
binary regardless of the initial mass ratio.

In order to determine the role hydrogen plays in the future dynamical evolution of the observed DWD merger systems, one can make a simple analytical estimate as to whether or not the donor WD will be quiescently burning at the onset of RLO. Using the core mass - luminosity relation (Paczynski 1970), Istrate et al. (2014) derive a timescale for hydrogen burning

$$t_p = 400 \text{ Myr} \left(\frac{0.2 M_{\odot}}{M_{\text{WD}}}\right)^7,$$

(1)

assuming, for simplicity, that all helium donor WDs have 0.01 $M_{\odot}$ of hydrogen mass available to burn in their envelopes.

One can then compare $t_p$ with the merging timescale as derived using the binary’s orbital parameters,

$$t_m = 9.838 \times 10^6 \text{ yr} \left(\frac{P_{\text{orb}}}{1 \text{ hr}}\right)^{8/3} \left(\frac{M_1 + M_2}{M_1 M_2}\right)^{1/3},$$

(2)

where $M_1$ and $M_2$ are measured in units of $M_{\odot}$.

Figure 1 shows the observed detached DWD population in the $M_1$-$M_2$ plane and the ratio $t_p/t_m$ given these simple assumptions. We find that a significant fraction (about 50%) of the systems observed today may contain donor stars which will still be burning hydrogen at the onset of RLO. The extended envelope of the donor may render it more susceptible to tidal feedback into the orbit and also will cause it to begin mass transferring at a larger separation.

These results point to the existence of a population of short period, accreting DWDs undergoing a period of stable mass transfer in which the period derivative is consistent with that expected from gravitational waves and a mass transfer evolution which is drastically different from that expected when the cold He WD donor solution is applied. This is particularly important for systems in which mass transfer is expected to be dynamically unstable. The two shortest orbital period binaries, HM Cancri and V407 Vulpeculae, exhibit this behavior (Marsh & Steeghs 2002; Israel et al. 2004; Barros et al. 2007), indicating that the duration of this unique phase of mass transfer is certainly non-negligible. The presence of hydrogen on the donor at the onset of mass transfer is clearly crucial to the stability of DWDs, which is in turn sensitive to the hydrogen burning temperature after the CE phase $t_p$, which has been derived here under very simplistic assumptions. In reality, the evolution of ELM He WDs with hydrogen burning envelopes is complicated by the effects of diffusion, gravitational settling, and other mixing processes. Additionally (and perhaps more importantly), some WD core masses encounter a thermal instability in the hydrogen burning layer, resulting in hydrogen shell flashes which are difficult to describe analytically. These complications motivate us to model the evolution of these objects numerically.

3. EVOLUTION OF HYDROGEN BURNING ELM WDs

3.1. Methods

ELM He WDs consist of an inert helium core and a tenuous outer layer. During the hydrogen shell burning phase, the conductive interior is nearly isothermal with a temperature given by the hydrogen burning temperature of $T_{\text{core}} \approx 10^8$ K and evolution takes place at nearly constant luminosity dictated by the core mass - luminosity relation.

To calculate the evolution of these ELM helium WDs with hydrogen envelopes, we use Modules for Experiments in Stellar Astrophysics (MESA) (Paxton et al. 2011, 2013) version 6794. We model helium WD formation by truncating a 1.0 $M_{\odot}$ star along the main sequence and removing mass. We then allow the inert core to come into diffusive equilibrium before allowing it to cool.

As seen in other theoretical studies, ELM WDs within a mass range of about 0.18-0.36 $M_{\odot}$ experience hydrogen CNO flashes due to a thermal instability induced by their geometrically thin burning shells (Webbink 1975; Althaus et al. 2001; Panei et al. 2007; Althaus et al. 2013; Gautschy 2013). The resulting runaway is quenched once the shell is no longer thin and leads to a rapid expansion of the stellar envelope. The WD may undergo several flashes until eventually the burning shell becomes too thin to maintain a sizable temperature perturbation and the WD burns the rest of its hydrogen stably. For WDs with masses either above or below the flashing range, the hydrogen content of the envelope is always burned quiescently until the WD joins the cooling sequence. In order to calibrate our models, we focus on the two known eclipsing detached DWDs, which fortunately happen to sample both sides of this evolutionary hydrogen burning dichotomy.

SDSS J0651+2844 is the shortest period detached binary discovered, with an orbital period of $P_{\text{orb}} = 12.75$ min (Brown et al. 2011) and provides an example of a system whose donor star lies within the flashing regime. The lower mass WD is found to have a mass of $M_2 \approx 0.25 M_{\odot}$ and a radius $R_2 \approx 0.0353 \pm 0.0004 R_{\odot}$, and the system is expected to come into contact through gravitational waves in a time $t_m = 0.9$ Myr.

A well studied example of a system that lies outside of the flashing regime, NLTT-11748, was discovered in 2009 as one of the first ELM WDs with subsequent radial velocity observations revealing modulation about an orbital period of $P_{\text{orb}} = 5.64$ h (Kawka & Vennes 2009; Kawka et al. 2010). In a search for radial pulsations within the lower mass WD, Steinfadt et al. (2010) discovered both primary and secondary eclipses within the system consistent with the measured orbital period. More recently, Kaplan et al. (2014) used UL-TRACAM observations to fit the eclipsing lightcurve. Their statistical analysis yields a WD mass of $M_1 = 0.17 \pm 0.013 M_{\odot}$ and a radius of $R_2 = 0.0428 \pm 0.005 R_{\odot}$. In addition
to providing model independent masses and radii for the system, Kaplan et al. (2014) are able to measure the temperature of the companion CO WD 7600 ± 120 K and thus estimate a cooling age of 1.6–1.7 Gyr. Figure 2 shows the evolutionary tracks of our models in the $\log g - T_{\text{eff}}$ plane, which successfully describe the the properties of the observed systems.

To calculate the past and future evolution due to gravitational radiation, we take the observed properties of the systems today ($M_1$, $M_2$, $P_{\text{orb}}$) and time evolve the Roche lobe using the equation for losses due to gravity waves

$$R_{L1:0}(t) = (-\alpha t + R_{L1:0}^2)^{1/4}$$

where $\alpha = 256G^3M_1M_2(M_1+M_2)/(5c^5)$ and $R_{L1:0}$ is the Roche lobe radius today, approximated analytically by Eggleton (1983) as

$$R_{L1:0} = \frac{0.49a_0^{2/3}}{0.6a_0^{1/3} + \ln(1 + q^{1/3})a_0}$$

where $a_0 = f(M_1, M_2, P_{\text{orb}})$ is the observed separation today.

Here we denote $t = 0$ as the moment when our stellar model matches current observations of $\log g$ and $T_{\text{eff}}$. We are then able to look at the past history and future evolution of our donor model in tandem with the analytically describable evolution of the Roche lobe. Within this convention, reattachment takes place at a time $t > 0$ when $R_{L1}(t) = R_{L1}(t)$ (from MESA) and CE detachment occurs at a time $t < 0$ when the same condition is satisfied. Since we are using the formula for point masses, this assumes that tidal interactions are not important until mass transfer occurs.

3.2. Past Evolution: The Role of the CNO Flashes

For WDs which undergo CNO flashes, we find that the past history of hydrogen burning is quickly eradicated. Figure 3(a) shows the time evolution of hydrogen mass for two MESA WD models with the same total mass ($M_{\text{tot}} = M_{\text{env}} + M_{\text{core}} = 0.25 M_\odot$) but very different initial envelope masses converging within less than 1 Gyr. Because the WDs have the same total mass, this means that the observables today would be independent of the initial conditions. Figure 3(b) shows the evolution of $R_2$ and $R_{L1}$ of a J0651-like 0.25 $M_\odot$ WD undergoing CNO flashes. During the flashes $R_2 > R_{L1}$ and the ensuing mass transfer, which is not taken into account in our models, further prevents us from placing any constraints on the system’s conditions at CE detachment.

For hydrogen burning ELM WDs outside of this flashing regime, the radius of the donor is monotonically decreasing in time. Figure 4(a) demonstrates the lack of convergence in time for different initial hydrogen masses since burning remains quiescent throughout the evolution. This implies that an observation of WD mass and radius today allows us to uniquely constrain the hydrogen mass and use our stellar models to map back to the CE detachment given some independent estimate of its post CE age.

Since the cooling properties of CO WDs are much better calibrated and do not depend on the possibility of CNO flashes and the cooling time of an insulating H burning envelope, they provide us with a reliable estimate of the time since the system emerged from a CE. With this, we trace the evolution of a 0.17 $M_\odot$ WD with an initial hydrogen envelope mass of $1.1 \times 10^{-2}$ $M_\odot$ and find that $M_{\text{H}}(-t_{\text{cool}}) = 2.2 \times 10^{-3} M_\odot$.

Perhaps unsurprisingly, we find that we are unable to have our quiescently burning models in contact with the Roche lobe radius at the cooling age of the CO WD, regardless of the initial hydrogen mass. The solution to this ostensible paradox is to remember that during the CE phase there is a considerable injection of entropy onto the ELM WD, resulting in a substantial increase in radius. However, because of the relatively short thermal time of the envelope this entropy injection is almost immediately forgotten once the CE phase has ended. As a toy model, we modify MESA to artificially inject luminosity within the outer $10^{-3}$ $M_\odot$ of the WD in order to mimic the last phases of the CE in an NLTT-11748 like model and find that the CE phase must have provided a luminosity of about $L_{\text{CE}} \approx 8.6 \times 10^{14}$ erg s$^{-1}$ in order to have the WD in contact at the cooling age of the CO WD. Attribution this to an accretion luminosity, this corresponds to an accretion rate...
of $M = 5 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$ (Figure 4(b)).

3.3. Future Evolution: Conditions at the Onset of RLO

Because a hydrogen mass maps almost uniquely to a total stellar radius for a given total WD mass, we can use the observations of our two eclipsing systems today to infer their future evolution. In particular, we wish to investigate the thermal state of the donor at reattachment.

Figure 5 shows the composition, burning regions, and degeneracy parameter $\eta = E_F / k_B T$ as a function of radius for our model WDs at reattachment. At this stage, the 0.25 and 0.17 $M_\odot$ models have $6 \times 10^{-4}$ and $2 \times 10^{-3} \, M_\odot$ of hydrogen left, respectively, and are still undergoing hydrogen burning. Although the amount of mass in this burning envelope is minuscule, it results in a nearly 30% increase in radius for both stars which leads them to begin to transfer mass at larger separations. This extended envelope is also significantly non-degenerate due to the heat released by the burning, leading to an inversion of the typical cold WD mass-radius relation. This inversion renders the system stable regardless of the mass ratio and would likely result in an X-ray emitting, low frequency gravitational wave source. The duration of this phase of mass transfer depends sensitively on the interplay between gravitational wave losses, hydrogen burning lifetime of the donor, response of the accretor (Shen 2015), and tidal torques which we plan to explore in a subsequent paper using the framework outlined in Gokhale et al. (2007).

4. DISCUSSION

In this Letter, we have demonstrated a method of combining stellar evolution models in tandem with standard GW calculations to infer the past and future evolution of currently detached DWD binaries. Using this method we are for the first time able to put constraints on donor conditions such as envelope mass and luminosity immediately proceeding the CE given the current separation, masses, and donor radii of these detached DWDs, assuming they are not within the flashing regime and have a reliable cooling age for the higher mass WD. Regardless of the presence of flashes, we are able to say whether or not the donor will be actively burning hydrogen at the onset of mass transfer and thus whether standard stabili-
The Past and Future of DWDs

Figure 5. Radial composition of the donor star in J0651 ($M_2 = 0.25 M_\odot$) and NLTT-11748 ($M_2 = 0.17 M_\odot$) at the time of reattachment (left and right panels, respectively). The black and green dotted lines show the specific energy generation rate and dimensionless degeneracy parameter $\eta$, respectively. In both systems, it is clear that the hydrogen burning envelope remains active until reattachment.

ity calculations can predict if the system will truly merge at contact.

We find that roughly half of the currently observed detached DWDs may begin mass transferring when the donor is still burning hydrogen, resulting in larger separations at the onset of mass transfer, lower accretion rates, and a period derivative consistent with evolution driven by gravitational radiation. Self-consistently modeling of the resulting mass transfer for these systems is required to infer the lifetime of the non-degenerate, hydrogen-rich mass transfer phase, which in turn is essential for predicting the number of X-ray and low frequency gravitational wave sources. The properties of the surviving population depend critically on the interplay of these physical processes and can be used to constrain them. To this end, a detailed study of the stabilizing effect of tidal interactions during this mass transfer phase is needed, as the current $10^6$ yr lifetime predicted by D’Antona et al. (2006) and Kaplan et al. (2012) appears to be too short to explain the presence of HM Cancri and V407 Vulpeculae.

While the current number of DWDs in which the donor radius is known is small due to the necessity of an eclipse, Gaia will greatly increase this sample by accurately determining the distance to many systems (Holberg et al. 2012). By applying this technique to a population of DWDs with accurate donor radii one can statistically constrain the conditions at CE detachment, enabling statistical studies that can help gain insight into the formation of compact binaries.

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