CARBON SHELL OR CORE IGNITIONS IN WHITE DWARFS ACCRETING FROM HELIUM STARS

JARED BROOKS1, LARS BILDSTEN1,2, JOSIAH SCHWAB3,4, AND BILL PAXTON2

1 Department of Physics, University of California, Santa Barbara, CA 93106, USA
2 Kavli Institute for Theoretical Physics, Santa Barbara, CA 93106, USA
3 Physics Department, University of California, Berkeley, CA 94720, USA
4 Astronomy Department and Theoretical Astrophysics Center, University of California, Berkeley, CA 94720, USA

ABSTRACT

White dwarfs accreting from helium stars can stably burn at the accreted rate and avoid the challenge of mass loss associated with unstable helium burning that is a concern for many SNe Ia scenarios. We study binaries with helium stars of mass $1.25M_\odot \leq M_{\text{He}} \leq 1.8M_\odot$, which have lost their hydrogen rich envelopes in an earlier common envelope event and now orbit with periods ($P_{\text{orb}}$) of several hours with non-rotating $0.84$ and $1.0M_\odot$ C/O WDs. The helium stars fill their Roche lobes after exhaustion of central helium and donate helium on their thermal timescales ($\sim 10^3$ years). As shown by others, these mass transfer rates coincide with the steady helium burning range for WDs, and grow the WD core up to near the Chandrasekhar mass ($M_{\text{Ch}}$) and a core carbon ignition. We show here, however, that many of these scenarios lead to an ignition of hot carbon ashes near the outer edge of the WD and an inward going carbon flame that does not cause an explosive outcome. For $P_{\text{orb}} = 3$ hr, $1.0M_\odot$ C/O WDs with donor masses $M_{\text{He}} \gtrsim 1.8M_\odot$ experience a shell carbon ignition, while $M_{\text{He}} \lesssim 1.3M_\odot$ will fall below the steady helium burning range and undergo helium flashes before reaching core C ignition. Those with $1.3M_\odot \lesssim M_{\text{He}} \lesssim 1.7M_\odot$ will experience a core C ignition. We also calculate the retention fraction of accreted helium when the accretion rate leads to recurrent weak helium flashes.

Key words: binaries: close – supernovae: general – white dwarfs

1. INTRODUCTION

The possible progenitor systems for SNe Ia presently fall into two categories: the single degenerate and double degenerate scenarios, each with theoretical challenges. The double degenerate scenario, characterized by the merger of two WDs that unstably ignites degenerate carbon, is challenged because an off-center ignition of carbon likely converts C/O WDs to O/Ne WDs via an inwardly propagating carbon flame (Nomoto & Iben 1985; Saio & Nomoto 1985, 1998; Woosley & Weaver 1986; Shen et al. 2012). Recent 3D simulations of these mergers found a prompt detonation can be triggered during the merger process when the mass ratio is close to unity (Pakmor et al. 2010, 2011, 2012; Ruiter et al. 2013). The single degenerate scenario, characterized by stable accretion onto WDs until they grow to the Chandrasekhar mass ($M_{\text{Ch}}$), is challenged by many theoretical and observational issues, including hydrogen flashes, or flashes of the helium built up via steady hydrogen burning, which remove mass, possibly preventing efficient growth of the core (Iben & Tutukov 1989; Nomoto et al. 2007; Wolf et al. 2013). Included in the single degenerate scenario, however, are systems with helium star donors of mass $M_{\text{He}} \approx 1.2$–$1.8M_\odot$ that donate He-rich matter to WDs at $\dot{M} > 10^{-6}M_\odot$ yr$^{-1}$. This avoids hydrogen flashes, and, given a certain range of helium star masses, can allow for steady helium burning on the surface of the WD at the rate that it is accreted (Yoon & Langer 2003; Shen & Bildsten 2007; Piersanti et al. 2014), leading to steady growth of the WD core and a possible core carbon ignition. However, at these large $\dot{M}$'s, another possible outcome is a shell ignition of carbon that will non-explosively convert a C/O WD to an O/Ne WD, leading eventually to an accretion induced collapse (AIC) rather than a SN Ia (Nomoto & Iben 1985; Saio & Nomoto 1985, 1998).

Wang et al. (2009) explore this channel using an optically thick wind model (Hachisu et al. 1996), instead of solving the stellar structure equations of the accreting WDs. They find the area in the initial orbital period–$M_{\text{He}}$ plane where binary systems with these initial parameters will end in core ignitions. Assuming that the core ignitions lead to Type Ia SNe, they perform binary population synthesis (BPS) studies and calculate the birthrate of SNe Ia. By not solving the stellar structure equations of the WDs, however, they do not take into account the possibility of non-explosive shell carbon ignition. As we show, the effect of including this possibility shrinks the area in the log $P_{\text{orb}},M_{\text{He}}$ plane that leads to SNe Ia, and lowers the estimated SNe Ia rate through this channel.

In Section 2 we calculate the boundaries for steady helium burning accretion rates using MESA (Paxton et al. 2011, 2013, 2015), and explain the behavior of the models above and below the steady helium burning range. Then in Section 3 we explore the behavior of the core as it grows to core ignition near $M_{\text{Ch}}$ and explain the “race” to ignition between carbon the core and in the shell. We include in Section 4 a discussion on the effects of neutrino cooling in the cores of the WDs, discuss the possible observables from these systems in Section 5, and explore a low mass binary case that leads to a double degenerate scenario in Section 6. We conclude in Section 7.

2. STEADY HELIUM BURNING

When binary systems have high mass helium star donors ($1.3M_\odot \leq M_{\text{He}} \leq 1.8M_\odot$) the mass transfer is driven by the expansion of the donor as core helium is exhausted and the star leaves the He-main sequence. This allows for mass transfer rates that cross the regime for steady He burning (Piersanti et al. 2014).
The Astrophysical Journal, 821:28 (8pp), 2016 April 10

1.25 effective damped. Values above a certain accretion rate the oscillations in the burning rate are

Figure 1. Nuclear burning rates for a narrow set of accretion rates near the lower stability boundary for a 1.25M⊙ WD. Starting from a stable burning model at M_{WD} = 3.5 × 10^{-6} M⊙ yr^{-1}, the accretion rate is lowered to show values. Above a certain accretion rate the oscillations in the burning rate are effectively damped.

2.1. Calculation of Steady He-burning Boundaries

The steady burning boundaries are calculated using MESA (r7624) by taking a set of WD models that span the mass range [0.8,1.397] M⊙ and running them each with various M’s. We first create a steady burning model for each mass by setting an M in the middle of the steady burning zone from Piersanti et al. (2014), calculating through the first burst and allowing the burning rate to stabilize. The example case shown in Figures 1 and 2 is for a 1.25M⊙ model that starts with M_{WD} = 3.5 × 10^{-6} M⊙ yr^{-1}. Then we lower the accretion rate until the burning rate, L_{acc}, begins to oscillate by more than 15 per cent, and use this accretion rate as the lower steady burning boundary.

The lower stability boundary exists because at lower accretion rates, the helium shell has a lower temperature and higher density. When the accretion rate is lowered beneath the lower stability boundary, the heating timescale drops below the time required for the shell to adjust its thermal structure and a temporary runaway occurs. Above this boundary, the shell is hotter and less dense such that the thermal structure can adjust quickly enough in response to helium ignition, so nuclear burning rates are able to stabilize, as shown in Figure 1.

To find the upper steady burning boundary, we raise the accretion rate until the surface radius experiences rapid expansion. Increasing the accretion rate discontinuously, as we have done here, will naturally increase the surface radius, but only by a factor of order unity. Due to the core mass–luminosity relation (Paczynski 1971), there exists a maximum luminosity at which it can burn, and therefore a maximum accretion rate (Shen & Bildsten 2007). Once the accretion rate increases above this threshold, mass builds up in the shell and the WD either enters the RG regime (Piersanti et al. 2014) or drives an optically thick wind (Hachisu et al. 1999), both resulting in the rapid expansion of the surface radius by a few orders of magnitude, as shown in Figure 2.

2.2. He Burning During Binary Evolution

While the system is in the regime for steady He burning, the WD is burning helium to carbon and oxygen at the same rate that it is accreting helium. As the mass transfer rates rise above the steady burning regime, the WD rapidly expands into its Roche lobe (RL) and only accepts mass at the maximum steady burning rate. The rest of the mass is lost from the system such that M_{WD} + M_{wind} = -M_{dot}, where M_{wind} is the rate of mass loss from the binary system, as shown by the difference between the dotted and solid lines in Figure 3.

We compute M_{wind} by attenuating the mass transfer efficiency as the WD expands into a significant fraction of its RL. The shape of the mass transfer efficiency versus R_{WL}/R_{WL} has little effect on the M accepted by the WD due to the high sensitivity of the WD radius to the accretion rate near the upper stability boundary, as shown in Figure 2. The dynamic range of radii within the steady helium burning regime is relatively small compared to that near the upper stability boundary. We compare this method with that used in Yoon & Langer (2003) who used a radiation driven wind using M = 10^{-2} R_{WD} L_{WD}/[IGM_{WD}(1 - \Gamma)], where R_{WD}, L_{WD}, and M_{WD} are the radius, luminosity, and mass of the WD, and \Gamma is the ratio of photospheric luminosity to the Eddington luminosity. For their model starting with M_{WD} = 1.0M⊙, M_{He} = 1.6M⊙, when M_{WD} = 1.04M⊙ the wind reaches a maximum of 4.8 × 10^{-6} M⊙ yr^{-1}. In our model with the same initial conditions, at the corresponding point in evolution, we calculate a maximum wind rate of 4.2 × 10^{-6} M⊙ yr^{-1}, which is comparable.

The system mass loss increases the orbital separation, and thus acts to reduce the rapid mass transfer rates. We assume that the mass loss from the system takes with it the specific angular momentum of the WD, and we address the validity of this assumption in Section 2.3. When mass transfer rates fall...
The mass transfer rate from the helium star due to Roche lobe overflow (RLOF) is computed using the “Ritter” implicit scheme of MESA (Paxton et al. 2015), which computes the prescription given by Ritter (1988).

### 2.3. Angular Momentum Loss in Winds

We now address the validity of the assumption that the mass loss from the system takes with it the specific angular momentum of the WD. It is perfectly valid if the wind leaves the system quickly without interacting with the binary after being launched off the WD’s surface.

If, however, the wind speed is low, then it gets gravitationally torqued by the stars as it leaves the system, extracting extra angular momentum from the orbits. Hachisu et al. (1999) explore this issue of the angular momentum evolution in a binary and parameterize the extraction of extra angular momentum from a slow wind. They first define the dimensionless quantity $l_{\text{wind}}$ as

$$l_{\text{wind}} = \frac{\mathbf{J}}{\dot{M}_{\text{wind}} a \Omega_{\text{orb}}}$$

where $\mathbf{J}$ is the total angular momentum, $\dot{M}$ is the mass loss rate of the system, $a$ is the binary separation, and $\Omega_{\text{orb}}$ is the orbital angular frequency. If, as per our assumption, the wind from the system takes with it the specific angular momentum of the WD, then

$$l_{\text{wind}} = \frac{q}{(1 + q)^2}$$

where $q$ is the mass ratio $M_{\text{He}}/M_{\text{WD}}$. If the wind is slow, on the other hand, it extracts more angular momentum, and thus $l_{\text{wind}}$ is larger.

The expression for $l_{\text{wind}}$ as given by Hachisu et al. (1999) is then

$$l_{\text{wind}} \approx \max \left[ 1.7 - 0.55 \left( \frac{v}{a \Omega_{\text{orb}}} \right)^2, \left( \frac{q}{1 + q} \right)^2 \right]$$

where $v$ is radial velocity of the wind near the RL surface.

We show in Figure 4 for the case with $M_{\text{WD}} = 1.0M_\odot$, $M_{\text{He}} = 1.6M_\odot$, the specific angular momentum of the WD with the blue dotted line, and the specific angular momentum of the wind leaving the WD surface with solid green. The orange, purple, and red solid lines are from Equation (1) assuming the left-hand side option in the square brackets in Equation (2) with wind speeds of 900, 1000, and 1050 km s$^{-1}$, respectively. This figure shows that if $v_{\text{wind}} \gtrsim 1000$ km s$^{-1}$, then our initial assumption that the mass loss from the system takes with it the specific angular momentum of the WD is valid. Lower wind velocities would extract extra angular momentum, thus decreasing the orbital period and increasing system mass loss rates. We did not consider that possibility for this initial exploration.

### 3. CORE AND ENVELOPE EVOLUTION

Here we return to describe the “race” between the core and the envelope as to which will ignite carbon first. We present example models that explore the different possible outcomes and thus the final fate of these systems.

We start with the case with the highest mass donor, and thus the highest accretion rates, for the entire accretion lifetime. In Figure 5 we show the evolution of the core and the carbon shell (tracked by maximum temperature) of the model with initial donor mass $M_{\text{He}} = 1.8M_\odot$. This case shows that high accretion rates dump more heat into the envelope than the compressionial
heat in the core, and the shell crosses \( \epsilon_{\nu} = \epsilon_{C+O} \) before the core. Shell carbon ignition occurs when the WD reaches a mass of \( 1.360 M_\odot \) at a mass coordinate of \( 1.349 M_\odot \), nearly at the surface.

On the low mass donor end, however, carbon may not ignite at all. The model with initial donor mass \( M_{\text{He}} = 1.3 M_\odot \) stays at lower accretion rates and falls far enough below the steady helium burning range that the mild helium oscillations become powerful enough to blow off mass. The blue dashed line shows how the maximum temperature in the shell will oscillate between the flashing helium burning shell and the hot, compressed C/O ashes below the burning layer. At these accretion rates, however, the accretion efficiency stays above 70%, allowing the WD to gain enough mass to trigger carbon ignition in the core. We compare our accreted mass retention efficiency calculated in the final stages of this model using super-Eddington winds to the analytical estimates of Kato & Hachisu (2004) and Wang et al. (2015) in Figure 7. Wang et al. (2015) used MESA (r3661) for their study, but used the default super-Eddington wind settings, whereas we triggered super-Eddington winds while the WD is still in a compact configuration in order to speed the computation. Systems with donor mass \( \approx 1.3 M_\odot \), therefore, will fall to lower accretion rates and efficiencies, and ultimately lose contact before a core ignition occurs. The components, now both C/O WDs, will spiral in due to GWR and contribute to the double-degenerate channel for SNe Ia, as discussed in Section 6.

Between the high and low mass donor limits is the region where core carbon ignitions occur. This is where the donor mass is high enough that the accretion rates do not fall too far below the stability boundary before \( M_{\text{Ch}} \) is reached, but also low enough that it avoids a carbon shell ignition from long sustained high accretion rates. A clear example of this is shown in Figure 8, with the trajectories of the core and envelope shown with profiles in \( \rho-T \) space for a system with \( M_{\text{He}} = 1.6 M_\odot \). In Figure 9 we show the composition and temperature profile when this model has grown to \( 1.31 M_\odot \), the same profile as that in Figure 8. As the C/O envelope is \( 0.31 M_\odot \), this shows that the base is at a temperature minimum,
and the temperature maximum in the envelope is only \( \sim 10^2 \) deep. The core ignition in these models indicates that they are likely SN Ia progenitors.

4. DEVIATIONS FROM ADIABATIC CORE COMPRESSION

The black dashed lines in the previous figures (Figures 5, 6, 8) show the WD core trajectory, which, at \( T \approx 2 \times 10^8 \) K, deviates from the adiabatic compression expected for such high \( M' \)'s. Since there is no time for heat transfer at these rapid accretion rates, it is the onset of neutrino cooling (Paczynski 1971) at a rate \( \epsilon_\nu \) that leads to this deviation. This impacts the shell-core race to carbon ignition and also hints at a possible sensitivity to the initial WD core temperature, which depends on the WD age at the time accretion starts.

It is when the neutrino cooling timescale, \( t_\nu = c_\nu T/\epsilon_\nu \), approaches the compressional timescale \( t_{\text{comp}} = (d \ln \rho / dt)^{-1} \) that the core no longer evolves adiabatically. To derive the resulting relations more rigorously, we start by writing the entropy change, \( ds \), in the form of Equation (A6) of Townsley & Bildsten (2004),

\[
\frac{ds}{k_B/\mu m_p} = \left( a \frac{d \ln T}{dt} - b \frac{d \ln \rho}{dt} \right),
\]

where \( k_B \) is Boltzmann’s constant, \( \mu \) is the mean molecular weight, \( m_p \) is the proton mass, \( a = 1.22 + 0.41T^{1/3} \), \( b = 0.91 + 0.14T^{1/3} \), and \( \Gamma = (Z\epsilon)^2/aT \) where \( a \) is the ion separation, and we set \( Z = 6.857 \) for an equal (by mass) mix of carbon and oxygen. We divide each side by \( dt \) and multiply by \( T \) to obtain

\[
-d\nu(\rho, T) = T \frac{ds}{dt} = \frac{k_B}{\mu m_p} \left( a \frac{d \ln T}{dt} - b \frac{d \ln \rho}{dt} \right). \tag{4}
\]

and then expand the second term on the right as

\[
\frac{d \ln \rho}{dt} = \frac{d \ln \rho}{d \ln M} \frac{d \ln M}{dt}. \tag{5}
\]

We use MESA to compute the steeply rising value of \( n = d \ln \rho / d \ln M \) as \( M \rightarrow M_{\text{Ch}} \).
then solve the resulting differential equation for \( T(t) \) given an initial temperature.

This results in evolutionary trajectories in the \( \rho - T \) plane that are shown in Figure 10 to converge to a common \( \rho - T \) line when neutrino cooling is dominant. This common line is one where the neutrino cooling timescale equals that of compression (shown as light gray curves in Figure 10). Cold initial conditions adiabatically rise in temperature until meeting the \( M \)-dependent trajectory, whereas hot initial conditions will cool to reach the attractor. Hence, a range of initial conditions will converge to the same trajectory given the same \( M \). The same convergence of the evolution of the central temperature and density was shown in Paczyński (1971) in the context of intermediate mass AGB stars. Paczyński (1971), however, only show one convergence line due to the core mass–luminosity relation. Much colder cores with lower accretion rates never reach regimes where neutrino cooling is strong enough to cause convergence, and so behave differently.

5. HR DIAGRAMS

We now explore the observability of these systems by following their trajectories through the HR diagram. We show the evolution of the donors in Figure 11, starting from ignition of helium in the core in the lower right-hand corner, and evolving to higher temperatures and luminosities along the helium MS. Once helium in the core has been exhausted, shown by the leftmost (hottest) point in the evolution, the envelopes of the helium donors begin to expand due to helium shell burning, causing \( T_{\text{eff}} \) to decrease and the luminosity to increase. The rise in luminosity is halted by the start of mass transfer as the helium stars’ envelopes expand into their RLs. The position of the donors in the HR diagram when the carbon ignites falls right in the most heavily populated region of Figure 4 of Wang et al. (2014), which plots distribution of donor stars in systems that achieved a core ignition through the helium star channel.

With initial orbital periods \( P_{\text{orb,0}} \) that are longer (shorter), the donors will have more (less) time and room to expand their envelopes until RLOF, leading to donor stars that are redder (bluer) and brighter (dimmer) when carbon ignites in the WD. This suggests a diagonal patch in the HR diagram for the state of donors. Wang et al. (2009) and Liu et al. (2010) find systems in which the donor star donated enough helium that the helium shell burning layer starts becoming exposed, leading to a rapid evolution to higher temperatures and luminosities. This requires systems with either lower mass donors, which will fall below the steady helium burning mass transfer rates, or lower mass WDs, which means that the WD will spend a longer time accreting and thus has a much higher likelihood of experiencing a carbon shell ignition before a core ignition. We also show, in Figure 12, the evolution of the WD accretors in the HR diagram. Due to the steady helium burning on the surface of the WDs, they are hot and bright enough to be classified as supersoft X-ray sources (SSS) (Iben & Tutukov 1994; Kahabka & van den Heuvel 1997). The WDs begin their evolution in the middle of Figure 12 at about \( \log T_{\text{eff}} = 5.75 \) and \( \log L/L_{\odot} = 4.4 \), but will be obscured by an optically thick wind until they reach the red marker, where mass transfer rates have decreased below the upper steady helium burning boundary and the transfer efficiency reaches unity. For the systems with the lowest mass donors \( (M_{\text{He}} = 1.3-1.5M_{\odot}) \), the mass transfer rates drop below the steady helium burning range near the end of their evolution. The range of oscillations of \( T_{\text{eff}} \) during the mild helium oscillations is less than a factor of two. The luminosity, however, changes by about an order of magnitude, on the timescale of \( \approx 5 \) years, so this should be visible to observers.
Note that in all six models, by the time the carbon ignites, the optically thick wind has been inactive for tens of thousands of years, meaning that there should be no nearby circumstellar material.

6. LOWER MASS BINARY CASE LEADING TO WD MERGERS

We now test our prescriptions against the calculations done by Ruiter et al. (2013) in their example case in Section 2.3. They start with 5.65 and 4.32M_☉ MS stars separated by 37R_☉. After the primary evolves to become a C/O WD and engages in a common envelope with the secondary as it exhausts core hydrogen, they are left with a 0.84M_☉ WD and 1.25M_☉ helium star separated by 1.74R_☉. These are the parameters we initialize, with the mass transfer history shown in Figure 13. We model the system until the He star loses contact and the stars spiral inward due to GWR and begin to merge. When the mass of the helium layer on the donor decreases down to 7 × 10^{-3}M_☉, the helium burning layer becomes too weak to support an extended convective envelope and the surface contracts below the RL. Compared to Ruiter et al. (2013), we calculate less system mass loss, resulting in slightly more massive components, M_{WD} = 1.21M_☉, M_{He} = 0.81M_☉, compared to M_{WD} = 1.19M_☉, M_{He} = 0.77M_☉ for Ruiter et al. (2013). This also leads to a shorter merger time, 625 Myr for our work and 1130 Myr for Ruiter et al. (2013), after loss of contact.

As Ruiter et al. (2013) used the accumulation efficiencies of Kato & Hachisu (2004) for helium accretion onto WDs, this serves as an additional comparison (along with Figure 7) to the mass transfer prescriptions of Kato & Hachisu (2004). This shows that for WDs in the 1.2M_☉ range the Kato & Hachisu (2004) prescription match our ending masses to within a few per cent, but somewhat larger discrepancies appear for masses closer to M_{Ch} (Figure 7).

7. CONCLUSIONS

We ran binary simulations using MESA for WD + helium star systems, calculating stellar structure equations for both stars simultaneously, along with the binary parameters that take into account their interaction through mass transfer. The systems we study include 1.0M_☉ C/O WDs in 3 hr orbital periods (P_{orb}) with helium stars with masses 1.3M_☉ ≤ M_{He} ≤ 1.8M_☉. This configuration allows the steady growth of the WD core mass via steady helium burning on the WD surface. At mass transfer rates above the steady helium burning range, we assume an optically thick wind that ejects all the donated mass above the maximum steady helium burning rate from the system. Below the steady helium burning range the WD begins mild helium oscillations.

During the initial turn on of mass transfer, the WD surface is initially cold and must be heated through several helium flashes until steady helium burning can begin. Using Figure 10 of Shen & Moore (2014), we conclude that all the first bursts on the 1.0M_☉ WD models are well below the detonation threshold, but the first burst on the lower mass 0.84M_☉ WD may support a detonation.

We assume that the mass that is lost from the system takes with it the specific angular momentum of the accretor, which is justified as long as the wind speeds exceed v_{wind} ≥ 1000 km s^{-1}. We note here that some orbital angular momentum may be lost in spinning up the accreting WD, which we did not explore in this study. During the optically thick wind phase, however, the accretion stream coming through L1 may not be able to form a disk in the extended RG envelope around the WD, and may become part of that envelope once it reached a depth at which the surrounding
density matches the stream density, thus preventing any angular momentum transfer to the WD. This way, the angular momentum of the accretion stream gets fed back into the orbit through tidal effects on the extended envelope. We leave this subject, as well as internal angular momentum transport, to future studies.

The systems with the lowest mass donors ($M_{\text{He}} = 1.3 - 1.4 M_\odot$) begin mild helium burning oscillations before the WD reaches $M_{\text{Ch}}$. Systems with $1.3 M_\odot \leq M_{\text{He}} \leq 1.7 M_\odot$ experience a core ignition in a $M_{\text{Ch}}$ WD. Systems with $M_{\text{He}} \geq 1.8 M_\odot$ experience a shell ignition of carbon in the helium burning ashes. The corresponding maximum helium star donor mass for lower initial mass WDs might be even lower, given that they must spend more time accreting to grow to $M_{\text{Ch}}$, but the birthrate from those systems, from Table 1 in Wang et al. (2009), is negligible compared to systems with higher mass WDs. This shell ignition is non-explosive and will lead to a thin carbon burning front that will propagate through the C/O WD all the way to the center, converting a C/O WD into an O/Ne WD (Nomoto & Iben 1985; Saio & Nomoto 1985, 1998; Timmes et al. 1994). Without any carbon in the center, when the WD mass nears $M_{\text{Ch}}$, electron captures onto $^{28}\text{Mg}$ and $^{26}\text{Ne}$ will remove pressure support from the core, resulting in an accretion induce collapse (AIC), leaving behind a neutron star (Miyaji et al. 1980; Schwab et al. 2015). In future studies, we intend to run simulations over a large range of initial orbital periods and WD masses to determine the real upper boundary for the He star donor mass that allows a core ignition in the log $P_{\text{orb},0} - M_{\text{He}}$ plane in Figure 7 in Wang et al. (2009). In addition to changing the expected SN Ia rate, this would yield an AIC rate for this new channel (J. Brooks et al. 2016, in preparation). This would be in addition to the rate expected from the initially more massive, presumably O/Ne WD accretors.

Systems with $M_{\text{WD}} \gtrsim 1.1 M_\odot$, although assigned a much higher contribution to the SNe Ia birthrate than their lower mass WD counterparts, are not likely to be C/O WDs (Nomoto 1984; Timmes et al. 1994; Ritossa et al. 1996; García-Berro et al. 1997). Wang et al. (2014) explore systems with so-called “hybrid” C/O/Ne WDs that experience an off-center carbon ignition during WD formation that was quenched by convective boundary mixing and left an unburnt carbon oxygen core of up to $0.3 M_\odot$, surrounded by an O/Ne mantle of equal or greater mass (Denissenkov et al. 2013, 2015; Chen et al. 2014; this opens up the possibility that carbon shell ignitions on C/O WDs may experience flame quenching before converting the entire core into O/Ne). This thick O/Ne mantle would prevent carbon flames that ignited in the ashes from steady helium burning from reaching the unburnt core carbon. Therefore, carbon shell ignitions, like the one experienced by the WD with the $M_{\text{He}} = 1.8 M_\odot$ in this study, will not prevent hybrid C/O/Ne WDs from achieving core carbon ignition. It is unlikely, however, that this sort of WD can lead to a normal SN Ia because a deflagration ignited in the C/O core cannot transition into a detonation in the O/Ne mantle easily because the critical mass for a detonation of an O/Ne mixture is much larger than that of carbon (Denissenkov et al. 2015). These hybrid C/O/Ne WDs are more likely to lead to the subclass SN Iax (Fink et al. 2013; Kromer et al. 2015).

We also found that, due to rapid neutrino cooling in warm and dense cores, evolution of the central temperature and density will converge to accretion-rate dependent trajectories until ignition, given a high enough initial central temperature.

We acknowledge stimulating workshops at Sky House where these ideas germinated. We thank Ken Shen for helpful discussions regarding binary configurations. This work was supported by the National Science Foundation under grants PHY 11-25915, AST 11-09174, and AST 12-05574. J.S. is supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE 11-06400 and by NSF Grant No. AST 12-05732. Most of the simulations for this work were made possible by the Triton Resource, a high-performance research computing system operated by the San Diego Supercomputer Center at UC San Diego.

REFERENCES

Chen, M. C., Herwig, F., Denissenkov, P. A., & Paxton, B. 2014, MNRAS, 440, 1274

Denissenkov, P. A., Herwig, F., Truran, J. W., & Paxton, B. 2013, ApJ, 772, 37

Denissenkov, P. A., Truran, J. W., Herwig, F., et al. 2015, MNRAS, 447, 2596

Fink, M., Kromer, M., Seitenzahl, I. R., et al. 2013, MNRAS, 438, 1762

García-Berro, E., Ritossa, C., & Iben, I. 1997, ApJ, 485, 765

Hachisu, I., Kato, M., & Nomoto, K. 1996, ApJL, 470, L97

Hachisu, I., Kato, M., & Nomoto, K. 1999, ApJ, 522, 487

Iben, I. J., & Tutukov, A. V. 1989, ApJ, 342, 430

Iben, I. J., & Tutukov, A. V. 1994, ApJ, 431, 264

Kahabka, P., & van den Heuvel, E. P. J. 1997, ARA&A, 35, 69

Kato, M., & Hachisu, I. 2004, ApJL, 613, L129

Kromer, M., Ohlmann, S. T., Pakmor, R., et al. 2015, arXiv:1503.04292

Liu, W.-M., Chen, W.-C., Wang, B., & Han, Z. W. 2010, A&A, 523, A3

Miyaji, S., Sugimoto, D., Nomoto, K., & Yokoi, K. 1980, ICRC, 2, 13

Nomoto, K. 1984, ApJ, 277, 791

Nomoto, K., & Iben, I. J. 1985, ApJ, 297, 531

Nomoto, K., Saio, H., Kato, M., & Hachisu, I. 2007, ApJ, 663, 1269

Paczynski, B. 1971, AcA, 21, 271

Pakmor, R., Hachinger, S., Köpke, F. K., & Hillebrandt, W. 2011, A&A, 528, A117

Pakmor, R., Kromer, M., Röpke, F. K., et al. 2010, Natur, 463, 61

Pakmor, R., Kromer, M., Taubenberger, S., et al. 2012, ApJL, 747, L10

Paxton, B., Bildsten, L., Dotter, A., et al. 2011, ApJS, 192, 3

Paxton, B., Cantwell, M., Arras, P., et al. 2013, ApJS, 208, 4

Paxton, B., Marchant, P., Schwab, J., et al. 2015, ApJS, 220, 15

Piersanti, L., Tornambè, A., & Yungelson, L. R. 2014, MNRAS, 445, 3239

Riotti, C., García-Berro, E., & Iben, I. J. 1996, ApJ, 460, 489

Ritter, H. 1988, A&A, 202, 93

Rutte, J. A., Sim, S. A., Pakmor, R., et al. 2013, MNRAS, 429, 1425

Saio, H., & Nomoto, K. 1995, A&A, 150, L21

Saio, H., & Nomoto, K. 1998, A&A, 330, L37

Schwab, J., Quataert, E., & Bildsten, L. 2015, MNRAS, 453, 1910

Shen, K. J., & Bildsten, L. 2007, ApJ, 660, 1444

Shen, K. J., Bildsten, L., Kasen, D., & Quataert, E. 2012, ApJ, 748, 35

Shen, K. J., & Moore, K. 2014, ApJ, 797, 46

Timmes, F. X., Woosley, S. E., & Taam, R. E. 1994, ApJ, 420, 348

Townsley, D. M., & Bildsten, L. 2004, ApJ, 600, 390

Wang, B., Li, Y., Ma, X., et al. 2015, A&A, 584, A37

Wang, B., Meng, X., Chen, X., & Han, Z. 2009, MNRAS, 395, 847

Wang, B., Meng, X., Liu, D.-D., Liu, Z.-W., & Han, Z. 2014, ApJL, 794, L28

Wolf, W. M., Bildsten, L., Brooks, J., & Paxton, B. 2013, ApJ, 777, 136

Woosley, S. E., Taam, R. E., & Weaver, T. A. 1986, ApJ, 301, 601

Yoon, S.-C., & Langer, N. 2003, A&A, 412, L53