

# Pre-explosion Properties of Helium Star Donors to Thermonuclear Supernovae

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## Abstract

Helium star-carbon-oxygen white dwarf (CO WD) binaries are potential single-degenerate progenitor systems of thermonuclear supernovae. Revisiting a set of binary evolution calculations using the stellar evolution code MESA, we refine our previous predictions about which systems can lead to a thermonuclear supernova and then characterize the properties of the helium star donor at the time of explosion. We convert these model properties to near-UV/optical magnitudes assuming a blackbody spectrum and support this approach using a matched stellar atmosphere model. These models will be valuable to compare with pre-explosion imaging for future supernovae, though we emphasize the observational difficulty of detecting extremely blue companions. The pre-explosion source detected in association with SN 2012Z has been interpreted as a helium star binary containing an initially ultra-massive WD in a multiday orbit. However, extending our binary models to initial CO WD masses of up to 1.2  $M_{\odot}$ , we find that these systems undergo off-center carbon ignitions and thus are not expected to produce thermonuclear supernovae. This tension suggests that, if SN 2012Z is associated with a helium star-WD binary, then the pre-explosion optical light from the system must be significantly modified by the binary environment and/ or the WD does not have a carbon-rich interior composition.

Unified Astronomy Thesaurus concepts: Supernovae (1668); White dwarf stars (1799); Helium-rich stars (715); Close binary stars (254)

Supporting material: machine-readable tables

#### 1. Introduction

Close helium star (He star)-carbon-oxygen white dwarf (CO WD) binaries are potential progenitors of thermonuclear supernovae (TN SNe; e.g., Iben & Tutukov 1994). For He stars  $\approx 1-2$  $M_{\odot}$ , thermal timescale mass transfer initiated during their subgiant or giant phases occurs at rates  $\sim 10^{-6} M_{\odot} \,\mathrm{yr}^{-1}$  such that the accreted He can be burned in a thermally stable configuration on the WD (e.g., Nomoto 1982). Because this implies that the WD can efficiently grow, He star-CO WD binaries are a promising single-degenerate, Chandrasekhar-mass (M<sub>Ch</sub>) TN SN channel (Yoon & Langer 2003; Wang et al. 2009b; Brooks et al. 2016; Wang et al. 2017).<sup>5</sup> This has gained popularity as a progenitor channel for Type Iax supernovae, under the assumption that the CO WD explodes in a pure deflagration (e.g., Kromer et al. 2013; Long et al. 2014; Jha 2017). The necessarily short orbital periods of these binaries also provide a mechanism for producing the high velocities of an emerging population of peculiar stellar objects that may be the partially disrupted WD remnants of these explosions (Vennes et al. 2017; Raddi et al. 2018a, 2018b, 2019).

Because this channel invokes the presence of a luminous, evolved He star donor, pre-explosion imaging of observed TN SNe can provide a powerful test of the scenario. A luminous blue point source is present at the location of the type Iax supernova SN 2012Z in Hubble Space Telescope (HST) pre-explosion images of its host galaxy NGC 1309 (McCully et al. 2014). The properties of the pre-explosion source do not allow for an unambiguous interpretation, but are consistent with He star-CO WD models from Liu et al. (2010). Only one other Type Iax supernova, SN 2014dt in M61, has comparable pre-explosion limits; in that case, no source was detected (Foley et al. 2015).

These and future observations motivate theoretical predictions for the range of He star donor properties expected at around the time of explosion. In Wong & Schwab (2019), we used stellar evolution calculations that resolve the stellar structures of both binary components to identify which He star-CO WD systems (in terms of initial WD mass, the initial He star mass, and initial orbital period) evolve to form TN SNe. These results were broadly consistent with previous work (Wang et al. 2009b, 2017), but the calculation of the WD evolution under a self-consistent, time-dependent mass-transfer rate allowed more accurate distinction between the eventual formation of TN SNe (via central ignition of carbon burning) and alternative outcomes (via off-center carbon ignition; Brooks et al. 2017; Wu & Wang 2019). However, the Wong & Schwab (2019) models elided a final phase of thermally unstable He shell burning (i.e., He novae) that occurs in many systems. Since the models did not cover this phase, they did not provide the He star properties at the time of explosion. Here, we revisit these systems with a modified computational approach that removes this restriction.

In Section 2, we describe our binary stellar evolution approach, which uses mass retention efficiencies for He accretion previously calculated by Kato & Hachisu (2004). In Section 3, we characterize the pre-explosion properties of our He star models. We compute the magnitudes and colors of these objects and check the assumption of blackbody emission against stellar atmosphere calculations. We compare with the source detected in coincidence with SN 2012Z (McCully et al.

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Another important He star-CO WD binary channel, which we do not discuss in this paper, involves lower He star masses  $\approx 0.4-1.0 \ M_{\odot}$ . These binaries have mass-transfer rates  $\sim 3 \times 10^{-8} \ M_{\odot} \ yr^{-1}$ , which can lead to accumulation of a He shell and its eventual detonation (e.g., Neunteufel et al. 2019, and references therein).



Figure 1. Fate of the He star–CO WD binaries as a function of initial He star mass  $(M_{He}^i)$  and initial orbital period  $(\log P_d^i)$ . Panel (a) shows a schematic of the final outcomes of the  $M_{WD}^i = 1.0 M_{\odot}$  grid from Wong & Schwab (2019). Shaded squares label possible outcomes and serve as a key to panel (b). The focus of this study is systems in/near the TN SN region, whose lower (dashed) boundary is dependent on the assumed average retention efficiency (drawn assuming an efficiency threshold of  $\approx 60\%$ ). For information on the other outcomes, see Wong & Schwab (2019). The light shaded background indicates the systems we re-simulate in this study. In panel (b), we color code the He flash systems by the required average retention efficiency ( $\bar{\mathcal{R}}_{req}$ ) for the WD to grow to  $M_{Ch}$ . Lower efficiencies (lighter) are more likely to be TN SNe. Note that some systems at the boundary between outcomes experienced effectively simultaneous core and shell ignitions and thus are marked as both.

2014) and with the models of Liu et al. (2010) and Liu et al. (2015). We similarly conclude that reproducing the source in 2012Z with a He star model appears to require a massive ( $\approx 1.2 M_{\odot}$ ) WD. In Section 4, we extend the Wong & Schwab (2019) models to CO WDs with this high mass and show that it is particularly hard for such systems to avoid off-center carbon ignition (meaning they would not produce TN SNe). In Section 5, we summarize and conclude.

# 2. Pre-explosion Evolution

The Wong & Schwab (2019) He star–CO WD binary models covered a range of initial CO WD masses ( $M_{WD}^i =$ 0.90–1.05  $M_{\odot}$ ), initial He star masses ( $M_{He}^i = 1.1-2.0 M_{\odot}$ ), and initial orbital periods ( $\log P_d^i = -1.3-0.0$ ). Computational constraints prevented following models that experience thermally unstable He burning through their many He shell flashes, where the highly super-Eddington conditions in the envelope lead to prohibitively small time steps.

Most systems that may eventually grow to  $M_{\rm Ch}$  experience flashes during the latter portion of mass transfer. Therefore, in Wong & Schwab (2019), we stop the binary calculations at the onset of these flashes and calculate the required average retention efficiency for the WD to grow up to a critical mass,  $M_{\rm Ex} = 1.38 \ M_{\odot} \approx M_{\rm Ch}$ , the approximate mass for core carbon ignition to occur in a nonrotating WD. The required average retention efficiency is defined as

$$\bar{\mathcal{R}}_{\rm req} = \frac{M_{\rm Ex} - M_{\rm WD}^{fs}}{M_{\rm He,env}^{fs}},\tag{1}$$

where  $M_{\text{He,env}}^{fs}$  is the envelope mass of the He star and  $M_{\text{WD}}^{fs}$  is the total mass of the WD, each evaluated when the He flashes first start after thermally stable mass transfer.

Under the simple but reasonable assumption of a 60% average retention efficiency, Wong & Schwab (2019) classified the final outcome of each binary system. Figure 1, panel (a) shows a schematic version of this classification for systems

with an initially  $1.0 M_{\odot}$  CO WD. We define the TN SN region as the portion of parameter space where we observe (or expect) the WD model to undergo a central carbon ignition as it approaches  $M_{\rm Ch}$ . The choice of retention efficiency affects the boundary indicated as a dashed line. Figure 1, panel (b) shows the required efficiencies, calculated via Equation (1).

Wong & Schwab (2019) could approximately identify which systems reach TN SNe, but could not determine the He star properties at the time of explosion for the systems that experience He shell flashes. This section describes how we resimulate these systems using point-mass accretors in order to determine the properties of the He stars when the WD explodes.

## 2.1. Methods

We simulate the binary evolution of a He star and a pointmass WD accretor using MESA version 10398 (Paxton et al. 2011, 2013, 2015, 2018, 2019), with initial binary parameters  $(M_{\text{He}}^{i}, M_{\text{WD}}^{i})$ , and  $\log P_{d}^{i}$ ) taken from the systems that eventually undergo helium flashes in Wong & Schwab (2019). We adopt the same MESA input options as Wong & Schwab (2019), ensuring that the He star evolution should be similar between the sets of calculations. We briefly recapitulate some of the key choices; for additional details, see Wong & Schwab (2019) and/or the publicly available MESA input files.<sup>6</sup>

The He star is created from He zero-age main sequence (ZAMS) models assuming Y = 0.98 and Z = 0.02. We adopt the OPAL Type 2 opacities (Iglesias & Rogers 1996) and employ the *predictive mixing* capacity of MESA (for details see Section 2 in Paxton et al. 2018) to locate the convective boundary during core He burning. For numerical convenience we use the MLT++ capacity of MESA to artificially enhance the efficiency of convection in radiation-dominated, near-Eddington conditions. This is particularly helpful as the systems begin to come out of contact, when the He star luminosity is highest

<sup>&</sup>lt;sup>6</sup> https://zenodo.org/record/5540004

$$\log P_{\rm d}^i = -1.1$$



Figure 2. Mass-transfer histories of the point-mass models for varying  $M_{\rm He}^i$  with fixed  $M_{\rm WD}^i = 1.0 M_{\odot}$  and  $\log P_{\rm d}^i = -1.1$ . The solid lines are  $M_{\rm WD}$  and dashed are  $|M_{\rm He}|$ . The orange lines represent one of the models with a resolved (i.e., non-point-mass) WD. Below  $M_{\rm low}$  we adopt the KH04 retention efficiency prescription.

and its He envelope is small (see Appendix C in Wong & Schwab 2019). For the binary evolution, we adopt the implicit Ritter mass-transfer scheme.<sup>7</sup> We assume orbital angular momentum loss due to gravitational wave radiation and that systemic mass loss carries the specific angular momentum of the WD accretor.

Point-mass models do not evolve the thermal structure of the WD and therefore require prescriptions to detect the occurrence of off-center carbon ignition and to handle the fate of the accreted He. To address the former, we only re-simulate the binaries from Wong & Schwab (2019) where there is not an off-center carbon ignition. To address the latter, we adopt existing prescriptions for He accretion in different regimes, as described in the following subsection and illustrated in Figure 2.

#### 2.1.1. Mass Retention Efficiency

The He star donates material at a rate  $\dot{M}_{\text{He}}$ , causing the WD to grow at a net rate  $\dot{M}_{\text{WD}}$ . The retention efficiency is the fraction of mass donated by the He star that is accreted by the WD, i.e.,  $\mathcal{R} = \dot{M}_{\text{WD}} / |\dot{M}_{\text{He}}|$ .

When the He star donates material at a rate where the WD can burn the He in thermally stable manner, the WD grows at the rate the material is donated (e.g., Nomoto 1982; Piersanti

et al. 2014). We indicate the boundaries of this region as  $\dot{M}_{\rm low}$ and  $\dot{M}_{\rm up}$ , noting that these values are function of  $M_{\rm WD}$ (see Figure 2). The values of  $\dot{M}_{\rm up}$  used in this work are numerically fitted from the models in Wong & Schwab (2019).<sup>8</sup> (We discuss the values of  $\dot{M}_{\rm low}$  later.) We assume that mass transfer is fully conservative ( $\mathcal{R} = 1$ ) when the mass-transfer rate is  $\dot{M}_{\rm low} \leq \dot{M}_{\rm He} \leq \dot{M}_{\rm up}$ .

When the He star donates material faster than the maximum rate at which it can be stably burned, we assume the WD grows at the maximum rate, i.e.,  $\dot{M}_{\rm WD} = \dot{M}_{\rm up}$  for  $\dot{M}_{\rm He} > \dot{M}_{\rm up}$  and thus  $\mathcal{R} = \dot{M}_{\rm up} / |\dot{M}_{\rm He}|$  (e.g., Hachisu & Kato 2001; Yoon & Langer 2003; Wang et al. 2009b). Physically, we assume that material is expelled from the accreting WD either as an isotropic wind or via polar outflows and the material therefore leaves the system with the specific angular momentum of the WD (a scheme also referred to as isotropic re-emission, see van den Heuvel 1994). Wong & Schwab (2019) demonstrated that which binary systems are predicted to undergo TN SNe is not sensitive to the assumed specific angular momentum of this material.

When the He star donates material at a rate below  $\dot{M}_{\rm low}$ , the He burning shell becomes thermally unstable, leading to He shell flashes that can eject material (i.e., He novae), yielding a mass-transfer efficiency less than unity. We use the prescription by Kato & Hachisu (2004), hereafter KH04 for  $\mathcal{R}$  during these flashes.

The KH04 retention efficiencies are based on their optically thick wind theory, where the wind is launched from the iron opacity bump (Iglesias & Rogers 1996). For a fixed WD mass

 $<sup>\</sup>overline{7}$  The assumptions about the structure of the near-Eddington envelope of the He star donor and choice of mass-transfer scheme can influence the behavior of the models at the longest orbital periods. While this can have some qualitative impact on the evolution of individual systems, the overall conclusions of this paper are not sensitive to this treatment. Because the purpose of this paper is to demonstrate the effect of extending the models of Wong & Schwab (2019), we continue to adopt the same treatment of the donor. This caveat to our models is described more fully in the Appendix.

<sup>&</sup>lt;sup>8</sup> This value of  $\dot{M}_{up}$  is slightly smaller than that of Nomoto (1982). See Section 5 of Wong & Schwab (2019) for detailed comparisons to past work.

Table 1Outcome of Models

$\overline{(M_{\text{He}}^i, M_{\text{WD}}^i, \log P_{\text{d}}^i)}$	$(M_{\rm He}^f, M_{\rm WD}^f, \log P_{\rm d}^f)$	$\bar{\mathcal{R}}_{sim}$	Outcome
(1.1, 0.90, -1.2)	(0.72, 1.19, -1.15)	0.70	DWD
(1.2, 0.90, -1.2)	(0.75, 1.27, -1.15)	0.71	DWD
(1.3, 0.90, -1.2)	(0.77, 1.36, -1.16)	0.81	DWD
(1.4, 0.90, -1.2)	$(0.83, M_{\rm Ex}, -1.21)$	0.91	TN SN
(1.5, 0.90, -1.2)	$(0.89, M_{\rm Ex}, -1.24)$	0.95	TN SN
(1.6, 0.90, -1.2)	$(0.92, M_{\rm Ex}, -1.27)$	0.97	TN SN
(1.7, 0.90, -1.2)	$(0.94, M_{\rm Ex}, -1.30)$	0.98	TN SN
(1.8, 0.90, -1.2)	$(0.96, M_{\rm Ex}, -1.34)$	0.98	TN SN
(1.9, 0.90, -1.2)	$(0.97, M_{\rm Ex}, -1.38)$	0.99	TN SN

**Note.** We Show (from left to right): The initial mass of the helium star, the initial mass of the WD, the initial period, the final mass of the helium star, the final mass of the WD, the final period, the average helium flash retention efficiency realized in the simulation, and the outcome of the model. The initial values refer to the values before mass transfer is initiated, while the final values refer to the values at the time either the WD explodes or the mass transfer has stopped. If the WD does not experience any helium flashes, the retention efficiency is set to 1. Table 1 is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content.

(This table is available in its entirety in machine-readable form.)

and accretion rate onto the WD, they follow one helium flash cycle by combining a sequence of static and steady-state wind solutions. Over the cycle, the ratio of burned material to ignition mass then gives the retention efficiency.

We apply the KH04 retention efficiencies to our point-mass models as follows. These retention efficiencies are only provided for discrete values of the WD mass  $M_{WD}^{\text{flash}}$ . For each  $M_{WD}^{\text{flash}}$ , the efficiency is a function of the accretion rate  $\dot{M}_{WD}$ , with an applicable range  $\dot{M}_{\min} \leq \dot{M}_{WD} \leq \dot{M}_{\text{low}}$ . If  $\dot{M}_{WD}$  is outside the applicable range (i.e.,  $\dot{M}_{WD} \leq \dot{M}_{\min}$ ), we assume a retention efficiency of  $\mathcal{R} = 0$ . For a given model WD mass  $M_{WD}$ , we use the fitting formula of the closest  $M_{WD}^{\text{flash}}$  where  $M_{WD}^{\text{flash}} \leq M_{WD}$  (i.e., for a 1.23  $M_{\odot}$  WD we adopt the formula for a 1.20  $M_{\odot}$  WD).

We note in passing that He retention efficiencies have also been published by Piersanti et al. (2014) and Wu et al. (2017). As the former extend only up to a WD mass of  $\approx 1 M_{\odot}$ , they cannot be applied in the evolution up to explosion. The latter assume that a super-Eddington wind can be driven during a He flash. Their wind mass-loss rate is calculated by assuming that the WD luminosity in excess of its Eddington luminosity gives the kinetic power of the wind (assumed to move at the escape velocity). The retention efficiency is then calculated over multiple helium flash cycles in MESA. In general, the Wu et al. (2017) retention efficiencies are lower than those of KH04 by a factor  $\approx 2$ . Therefore, our TN SNe region calculated with the KH04 prescription would likely be smaller than if calculated with the Wu et al. (2017) prescription.

In summary, we adopt the prescription

$$\dot{M}_{\text{He}} > \dot{M}_{\text{up}}: \ \mathcal{R} = \dot{M}_{\text{up}} / |\dot{M}_{\text{He}}|$$
$$\dot{M}_{\text{low}} < \dot{M}_{\text{He}} < \dot{M}_{\text{up}}: \ \mathcal{R} = 1$$
$$\dot{M}_{\text{min}} < \dot{M}_{\text{He}} < \dot{M}_{\text{low}}: \ \mathcal{R} = \mathcal{R}_{\text{KH04}}$$
$$\dot{M}_{\text{He}} < \dot{M}_{\text{min}}: \ \mathcal{R} = 0.$$
(2)
$$2.2. \ Results$$

We re-simulated all of the systems from Wong & Schwab (2019) that were halted at the onset of He shell flashes for the



Figure 3. Outcomes of our calculations with point-mass accretors. Half-colored points indicate systems that became detached double WDs. Fully colored points reached conditions for a TN SN. Hatched colored points indicate models consistent with either a TN SN or off-center ignition within errors. The color indicates the average He flash retention efficiency realized in the calculation.

 $M_{\rm WD}^i = 0.90, 0.95, 1.00, \text{ and } 1.05 M_{\odot}$  WDs. We summarize the properties of these models in Table 1.

Figure 2 shows the mass-transfer histories of models at  $\log P_{\rm d}^i = -1.1$ . The mass-transfer history of the  $M_{\rm He}^i = 1.6 M_{\odot}$  and resolved WD model (orange lines) is well reproduced by the corresponding point-mass model (yellow lines). Below  $\dot{M}_{\rm low}$ , the differences between  $\dot{M}_{\rm WD}$  and  $|\dot{M}_{\rm He}|$  reflect the assumed KH04 retention efficiencies. The discontinuities in  $\dot{M}_{\rm WD}$  are due to our piecewise interpolation in these efficiencies.

The final outcomes of our point-mass WD models are summarized in Figure 3. The systems that do reach  $M_{\rm Ex}$  ( $\approx M_{\rm Ch}$ ) are color coded by the He flash retention efficiency realized in the simulation, defined as

$$\bar{\mathcal{R}}_{\rm sim} = \frac{M_{\rm Ex} - M_{\rm WD}^{J^{\rm S}}}{M_{\rm He}^{f} - M_{\rm He}^{f^{\rm S}}},\tag{3}$$

where  $M_{WD}^{fs}$  and  $M_{He}^{fs}$  are the masses of the WD and He star, each evaluated when the He flashes start after thermally stable mass transfer, and where  $M_{He}^{f}$  is the He star mass when the WD reaches  $M_{Ex}$ . For systems that eventually form double-detached WDs, we similarly calculate a He flash retention efficiency, but with  $M_{WD}^{f}$  instead of  $M_{Ex}$ . The systems that we predict to explode have high realized retention fractions, with  $\bar{\mathcal{R}}_{sim} \gtrsim 0.8$ for the KH04 efficiencies. However, this is a necessary but not sufficient condition, as  $\bar{\mathcal{R}}_{sim}$  does not account for the growth of the CO core of the He star, which further depletes the He envelope mass available for mass transfer.

Figure 3 can be compared to panel (b) of Figure 1, which shows the required He flash efficiency  $\bar{\mathcal{R}}_{req}$ . Lower  $M_{He}^i$ typically leads to higher  $\bar{\mathcal{R}}_{req}$ , reflecting the smaller amount of He available to be donated. But lower  $M_{He}^i$  also leads to lower  $\dot{M}_{He}$ , and thus lower  $\bar{\mathcal{R}}_{sim}$ . These opposing trends lead to the lower limit in  $M_{He}^i$  to form an  $\approx M_{Ch}$  WD, occurring where  $\bar{\mathcal{R}}_{sim} \approx \bar{\mathcal{R}}_{req}$ . Compared to the more approximate result of Wong & Schwab (2019), the lower boundary of the TN SN region shifts to slightly higher  $M_{He}^i$ .



**Figure 4.** Kiel diagram (panel a) and H-R (panel b) for pre-explosion He star models. Different style points show label different initial WD masses. Wolf–Rayet stars span a similar range in log  $T_{\rm eff}$  and down to log( $T_{\rm eff}/K$ )  $\approx 4.0$ , but occupy an area above both plots with lower surface gravity (log( $g/cm s^{-2}$ )  $\lesssim 4.0$ ) and significantly higher luminosity (log( $L/L_{\odot}$ )  $\gtrsim 5.0$ ). Subdwarfs occupy an area below both plots with similar or higher surface gravity and lower luminosity.

 Table 2

 The Properties of the Stripped He Star Companions at the Time the WD Explodes

$(M_{\rm He}^i, M_{\rm WD}^i, \log P_{\rm d}^i)$	$M_{ m He}^f$ $[M_\odot]$	$\frac{\log_{10} L}{[\mathrm{L}_{\odot}]}$	$\frac{\log_{10} T_{\rm eff}}{[\rm K]}$	<i>R</i> [R <sub>☉</sub> ]	$\log_{10} g$ [cm s <sup>-2</sup> ]	$M_{ m He\ env}$ $[M_{\odot}]$	M <sub>F275W</sub> [mag]	M <sub>F336W</sub> [mag]	M <sub>F438W</sub> [mag]	M <sub>F555W</sub> [mag]	M <sub>F814W</sub> [mag]
(1.4, 0.90, -1.2)	0.83	3.59	4.92	0.29	5.42	0.18	0.15	0.54	1.03	1.40	2.25
(1.5, 0.90, -1.2)	0.89	3.59	4.93	0.29	5.48	0.21	0.19	0.59	1.08	1.45	2.30
(1.6, 0.90, -1.2)	0.92	3.66	4.95	0.28	5.52	0.20	0.18	0.58	1.07	1.45	2.30
(1.7, 0.90, -1.2)	0.94	3.72	4.98	0.27	5.56	0.18	0.19	0.59	1.09	1.47	2.32
(1.8, 0.90, -1.2)	0.96	3.84	5.02	0.25	5.61	0.14	0.16	0.57	1.07	1.46	2.31
$(1.4, 1.00, -0.8)^*$	0.98	3.84	4.82	0.64	4.81	0.23	-1.16	-0.79	-0.33	0.04	0.86

Note. We only show the properties of the helium stars in the systems that exploded in a TN SN. The magnitudes are absolute AB magnitudes and calculated assuming a blackbody spectrum. Table 2 is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content. (This table is available in its entirety in machine-readable form.)

# 3. The Pre-explosion Models

For each model in Table 1 indicated as a TN SN outcome using the KH04 retention efficiencies, Table 2 contains an entry describing the properties of the He stars at the time of explosion. They have masses ranging from 0.75–1.15  $M_{\odot}$  and remaining He envelope masses ranging from 0.06–0.55  $M_{\odot}$ . With increasing  $M_{WD}^i$ ,  $M_{He}^f$  is higher with a thicker helium envelope, as less mass is required to grow the WD up to  $M_{Ch}$ . Figure 4 shows the location of these models in the Kiel and Hertzsprung–Russell (H–R) diagrams. Most of the He stars have  $\log(g/\text{cm s}^{-2})$  between 4.5 and 5.5, while the lowest is around 4.0. The figure shows that  $\log(L/L_{\odot})$  ranges from 3.2-4.2 and  $T_{\text{eff}}$  ranges from  $\approx$ 50–100 kK. With increasing  $M_{WD}^i$ , g and  $T_{\text{eff}}$  are generally lower and L is generally higher.

The pre-explosion He star fills its Roche lobe, so its radius is largely determined by its initial orbital period log  $P_d^i$  since  $M_{\text{He}}^i$ and  $M_{\text{WD}}^i$  span a narrow range. As a result, models with the same log  $P_d^i$  lie approximately on the same line of constant radius on the H-R diagram (Figure 4, panel b), with small deviations originating from the  $\approx 0.1$  dex change in period due to mass transfer. For models with the same  $\log P_d^i$ , a higher  $M_{\text{He}}^i$ leads to a higher pre-explosion L and  $T_{\text{eff}}$ . On the other hand, with increasing  $M_{\text{WD}}^i$ , the TN SN region moves to lower  $M_{\text{He}}^i$ and extends to longer  $\log P_d^i$  (see Section 4.4, Wong & Schwab 2019). Therefore, as  $M_{\text{WD}}^i$  increases, the pre-explosion models move to lower L and  $T_{\text{eff}}$  with fixed  $\log P_d^i$ , and to higher L and lower  $T_{\text{eff}}$  with fixed  $M_{\text{He}}^i$ .

Wang & Han (2009) use the results of Wang et al. (2009b) along with binary population synthesis calculations to predict the donor properties at explosion. As discussed in detail in Wong & Schwab (2019), our results are in general agreement with their work. In terms of the pre-explosion donor properties, one can directly compare our Figure 4(a) with Figure 2 in Wang & Han (2009). The models span a similar range of g and  $T_{\rm eff}$ .

## 3.1. Pre-explosion Colors

The colors of these progenitor models in the years leading up to explosion are of particular interest because of the presence of



**Figure 5.** Color–magnitude diagrams for indicated WFC3/UVIS filters. The pre-explosion He star models shown in Figure 4 are indicated by open symbols. These models assume a blackbody spectrum. In the left panel, filled circles show the location of blackbodies with the indicated effective temperatures (via the color bar) and luminosities (via the two labeled sequences). For reference, the main sequence (solar metallicity, nonrotating models) from the MESA Isochrones and Stellar Tracks (MIST; Choi et al. 2016) and the approximate location of sdB stars are also shown. The right panel zooms in on the region indicated by the gray rectangle in the left panel. The black star indicates the *standard* spectral model from Section 3.2 and is connected to its corresponding blackbody model with a thin line.

a luminous blue point source in the HST pre-explosion image of the type Iax supernova SN 2012Z (McCully et al. 2014). We focus our spectral modeling on the He star since we expect that the accreting WD would have very high effective temperatures around  $\log(T_{\rm eff}/K) \approx 5.7-6$  (see Figure 2 of Brooks et al. 2016), such that the He star spectrum would dominate in optical wavelengths.

We use starkit and wsynphot to generate synthetic photometry for these objects assuming a blackbody spectrum.<sup>9</sup> We report absolute AB magnitudes and colors associated with the HST Wide Field Camera 3 (WFC3)/UVIS optical filters F275W, F336W, F438W, F555W, and F814W. This is motivated by the Legacy Extragalactic UV Survey (LEGUS), a treasury program that has observed 50 galaxies within 12 Mpc with this instrument (Calzetti et al. 2015). Such data is a potential source of pre-explosion imaging for future, nearby supernovae. Figure 5 shows color-magnitude diagrams for our pre-explosion sources.

The luminous helium star donors are sdO stars that sit blueward of main sequence but well above the sdBs of the extreme horizontal branch. They are brightest in the bluest filter F275W with absolute AB magnitudes of 0.5 to -3 mag and faintest in the red filter F814W with the absolute magnitudes of 2.5 to -1 mag (see Table 2). Since our pre-explosion models have  $T_{\rm eff} \gtrsim 50$  kK, the aforementioned filters are all on the Rayleigh–Jeans tail of the spectral energy distribution (SED; see Figure 6), meaning the colors vary little with  $T_{\rm eff}$ , with a F275W–F814W color of  $\approx -2$ .

For typical stellar crowding conditions, the LEGUS observations are designed to reach a depth of  $m_{\rm F275W} = 26.0$  (AB), with signal-to-noise ratio (S/N) ~ 6 (Calzetti et al. 2015). Since the LEGUS galaxies are mostly at distances  $\approx 4-10$  Mpc, this puts even our coolest models near the edge of detection. Calzetti et al. (2015) suggest this data set will provide approximately one corecollapse SN pre-explosion image per year. Given local supernova rates (e.g., Li et al. 2011; Foley et al. 2013), this suggests a thermonuclear supernova every few years and a decade-scale interval between SN Iax in this host sample. The additional extent of the HST archives makes the situation somewhat less gloomy, but it is clear that placing limits on extremely blue companions is a significant challenge.

As discussed in McCully et al. (2014), the observed source associated with SN 2012Z is roughly consistent with He star models from Liu et al. (2010), who explored the potential of the He star–WD evolutionary channel to produce super-Chandrase-khar explosions (via the inclusion of differential rotation in the WD). Our results for  $\approx M_{\rm Ch}$  models beginning from a 1.0  $M_{\odot}$  WD are in general agreement with their results (compare our Figure 4, panel (b) with their Figure 7). However, the Liu et al. (2010) models that are most consistent with the source in 2012Z are those that result from an initially 1.2  $M_{\odot}$  WD that explodes between 1.4 and 1.6  $M_{\odot}$  (shown in their Figure 6). These are the least blue, with  $T_{\rm eff} \sim 10^4$ K, allowing them match the observed colors and to reach the observed brightness in the optical bands.

Liu et al. (2015) perform a similar study using point-mass WD accretors. Their results for He star–CO WD systems (upper left panel of their Figure 2) agree with our results in Figure 4, panel (b). However, in order to match the properties of the source in 2012Z, they too require a more massive WD ( $\approx 1.2-1.3 M_{\odot}$ ). Their WD models are point masses, so do not have a composition. However, based on difficulties in producing CO WDs with  $\gtrsim 1.1 M_{\odot}$ , they interpret a WD of this mass to be more likely to be a hybrid CO/ONe WD.<sup>10</sup>

Motivated by the indications from these studies that a massive WD may be needed, we will extend the Wong & Schwab (2019) models to higher initial WD masses in Section 4.

 $<sup>^{10}</sup>$  Hybrid CO/ONe WDs have a ONe mantle overlaying an CO core and may form if mixing at the convective boundary of the inward-going carbon flame in a super asymptotic giant branch star quenches burning (Siess 2009; Denissenkov et al. 2013; Chen et al. 2014). There remain questions about whether convective mixing can extinguish the flame (Lecoanet et al. 2016).

<sup>&</sup>lt;sup>9</sup> Available at https://github.com/starkit/.



Figure 6. SED for the stripped He star marked in Table 2 at the time of explosion of the WD companion. We show the predictions from a detailed atmosphere model (standard, see Table 3) together with a blackbody curve. Above the plot, we show the transmission curves for HST/WFC optical filters, which are commonly used when searching for objects in pre-explosion images. Because the He stars are very hot, the filters capture the Rayleigh–Jeans part of the spectrum, in which the difference between the atmosphere model and blackbody curve is relatively small.



**Figure 7.** We compare the absolute AB magnitudes predicted from the different spectral models with that of a corresponding blackbody, all computed for the stripped He star marked in Table 2 and discussed in Section 3.2. In general, the blackbody predicts brighter optical emission than the spectral models, while the predicted colors are similar between the different models.

#### 3.2. The Predictions from Spectral Models

The true emergent spectrum from the photosphere of a He star is not a blackbody and it is therefore possible that the predictions for the pre-explosion photometry change if we account for a more realistic SED for the He stars. Here, we test how accurate the blackbody assumption is by comparing one spectral model computed for one of the stripped He star with its corresponding blackbody spectrum. For this, we use the 1D non-LTE radiative transfer code CMFGEN (Hillier 1990; Hillier & Miller 1998, version from 2017 May 5).

We choose to model the spectrum for a 0.98  $M_{\odot}$  stripped He star orbiting a  $M_{WD}^i = 1.0 M_{\odot}$  WD on a log  $P_d^i = -0.8$ day orbit at the time the WD explodes (the model is marked with a star in Table 2. We take the same approach as outlined in Götberg et al. (2017) and assume the surface properties computed with MESA as the conditions at the base of the stellar atmosphere (see also Groh et al. 2014). We then model the emerging spectrum after taking assumptions for the wind mass-loss rate, the wind speed, and wind clumping.

Stellar wind mass loss is known to significantly affect the emerging spectrum by, for example, blocking ionizing emission if the wind is optically thick or introducing strong emission features. The wind mass loss from He stars is poorly constrained since very few stars have been observed (see however Gies et al. 1998; Groh et al. 2008; Wang et al. 2018). Theoretical predictions suggest that the winds from He stars are weak (with mass-loss rates of  $\dot{M}_{\rm wind} \sim 10^{-9} - 10^{-7} M_{\odot} \text{ yr}^{-1}$ ) and relatively fast (with terminal wind speeds of  $v_{\infty} \gtrsim 1000 \text{ km s}^{-1}$ ) (e.g., Krtička et al. 2016; Vink 2017). The star we model has a luminosity of  $6.8 \times 10^3 L_{\odot}$ , a mass of  $0.98 M_{\odot}$ , and a radius of  $0.64 R_{\odot}$  at the time the WD exploded.<sup>11</sup> We further predicted a surface temperature of 65,300 K and surface gravity of  $\log(g/\mathrm{cm} \mathrm{s}^{-2}) = 4.8$  from the MESA calculation. Following the theoretical predictions, we assume a wind mass-loss rate of  $10^{-8} M_{\odot} \text{ yr}^{-1}$  and a terminal wind speed of  $1200 \text{ km s}^{-1}$  for the atmosphere modeling. We assume that the wind follows a nonstandard  $\beta$ -law with wind profile parameter,  $\beta$ , set to 1, and a somewhat clumpy wind with a volume filling factor of 0.5. For numerical reasons, we included a negligible amount of hydrogen in the atmosphere ( $X_{\text{H,s}} = 2.5 \times 10^{-11}$ ). We refer to this model as the standard model (see Table 3).

 $<sup>\</sup>frac{11}{11}$  This model was made during the earlier stages of this work, and so its properties differ slightly from that shown in Table 2.

Table 3

Stellar Properties and AB Magnitudes Predicted by a Blackbody and Atmosphere Models for the Stripped He Star Model  $M_{\text{He}}^f = 0.98 M_{\odot}$  at the Time the WD Explodes

Model	T <sub>eff</sub> [kK]	$\frac{\log_{10} g_{\rm eff}}{[\rm cm \ s^{-2}]}$	$\frac{v_{\infty}}{[\text{km s}^{-1}]}$	$\dot{M}_{ m wind}$ [ $M_{\odot}$ yr <sup>-1</sup> ]	M <sub>F275W</sub> [mag]	<i>M</i> <sub>F336W</sub> [mag]	<i>M</i> <sub>F438W</sub> [mag]	<i>M</i> <sub>F555W</sub> [mag]	M <sub>F814W</sub> [mag]
Blackbody	65.63	4.81	•••		-1.16	-0.79	-0.33	0.04	0.86
Standard	65.27	4.8	1200	$10^{-8}$	-0.91	-0.51	-0.04	0.31	1.17
Slow	65.27	4.8	600	$10^{-8}$	-0.91	-0.52	-0.04	0.3	1.16
Slower	65.27	4.8	300	$10^{-8}$	-0.91	-0.52	-0.04	0.31	1.16
More	65.27	4.8	1200	$10^{-7}$	-0.93	-0.59	-0.1	0.19	0.99
Extreme	65.25	4.8	300	$10^{-7}$	-0.97	-0.66	-0.23	0.02	0.71

Note. The effective temperature,  $T_{\rm eff}$ , and the effective surface gravity,  $\log_{10} g_{\rm eff}$ , are predicted from the photosphere at  $\tau = 2/3$  in the atmosphere models. The stripped He star has a luminosity of  $6.8 \times 10^3 L_{\odot}$ , a mass of 0.98  $M_{\odot}$ , and a radius of 0.64  $R_{\odot}$ .

We show the resulting SED for the standard model in Figure 6. The figure shows that the SED has a similar shape when the spectrum is carefully modeled compared to when a blackbody is assumed. The stellar wind is not sufficiently optically thick to significantly affect the shape of the part of the spectrum that the considered filters probe. The main difference in terms of photometrical estimates is that the spectral model predicts somewhat lower flux in the optical wavelengths compared to the blackbody, corresponding to a systematic difference of about 0.3 mag. The colors of the modeled spectrum and the blackbody assumption are therefore similar. We present the calculated absolute magnitudes for the HST filters in Table 3.

Since the wind properties of He stars are uncertain, we create four additional models by varying the mass-loss rates and/or the wind speed as presented in Table 3. In two models, we decrease the terminal wind speed to  $600 \,\mathrm{km \, s^{-1}}$  (slow) and  $300 \text{ km s}^{-1}$  (slower). In another model, we increase the wind mass-loss rate to  $10^{-7} M_{\odot} \text{ yr}^{-1}$ , but keep the wind speed at  $1200 \text{ km s}^{-1}$  (more). In the last model, we increase the wind mass-loss rate to  $10^{-7} M_{\odot} \text{ yr}^{-1}$  and decrease the terminal wind speed to  $300 \text{ km s}^{-1}$  (extreme). With slower winds or higher wind mass-loss rates, the wind becomes denser and therefore more optically thick. If the wind is sufficiently dense, the emission at longer wavelengths is enhanced and the color becomes redder. Investigating how the stellar wind affects the SED is therefore important for understanding the origin of objects that are redder than expected, such as the one observed in SN 2012Z.

However, we do not find a large difference in the photometrical magnitudes when varying the wind parameters (see Table 3). The largest difference is seen in the extreme model, with at maximum 0.46 mag difference compared to the standard model in the reddest band, but only 0.06 mag difference in the bluest band. The colors do not significantly change either, F438W-F555W is estimated between -0.25 mag and -0.35 mag, while F555W-F814W is estimated between -0.69 mag and -0.86 mag. This can also be seen in Figure 7 where the predictions for absolute magnitudes are displayed for the blackbody and the spectral models. Since we created models with large differences in the wind properties compared to what is expected for He stars with the given stellar properties, we can therefore consider that the wind from the He star is not sufficient for making the star as red as observed in SN 2012Z (see also Figure 5).

## 4. Models with Initially Massive WDs

In this section, we extend the models of Wong & Schwab (2019) to include more massive  $M_{\rm WD}^i = 1.10 M_{\odot}$  and 1.20  $M_{\odot}$  CO WDs and examine the occurrence off-center carbon ignitions.

In Wang & Han (2009), when the accretor is a more massive WD, systems with higher He star masses and longer initial periods are able to reach explosion (their Figure 8). Higher He star masses and longer initial periods lead to increased masstransfer rates, but since the WD is limited in the amount it can accept, the mass transfer becomes more nonconservative. This can be counterbalanced by the WD beginning closer to  $M_{\rm Ch}$ . However, accounting for off-center ignitions (which eliminates the systems that transfer mass at or above  $\dot{M}_{up}$  for most of their history) leaves only a narrow range of systems with  $M_{\rm He}^i \approx 1.1 M_{\odot}$  and initial periods out to 100 days (see Figure 8 in Wang et al. 2017). The He star luminosity lies in a narrow range, so in systems with a wider orbit, the larger Roche lobe allows for a lower effective temperature of the Roche-lobefilling He star donor. A similar line of reasoning leads Liu et al. (2015) require a massive WD in a binary with an orbital period  $\gtrsim 10$  days in order to match the properties of the pre-explosion source in SN 2012Z.

#### 4.1. Point-mass WD Binary Models

We first create a grid of binary models with a point-mass WD using the approach described in Section 2 and using the helium flash retention efficiencies of KH04. The resulting outcomes are shown in Panel (a) of Figure 8. The black boxes identify systems that form detached double WD binaries. In the other systems, the WD eventually reaches  $M_{\text{Ex}}$  ( $\approx M_{\text{Ch}}$ ). Based on the results of resolved CO WD models accreting at constant rates, Wang et al. (2017) propose that off-center carbon ignitions can be approximately detected by comparing the final mass-transfer rate to a critical value,  $\dot{M}_{\text{WD}} \ge \dot{M}_{\text{cr}} = 2.05 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ . Systems that satisfy this criterion are marked by gray boxes with black stripes. The remaining systems that do not satisfy the Wang et al. (2017) criterion are then designated as Chandrasekhar-mass central ignitions and indicated by red boxes.

Similar to the results of Wang et al. (2017), the point-mass grid suggests that an initially 1.20  $M_{\odot}$  CO WD may undergo central ignition for an orbital period up to  $\approx$ 30 days. These long-period systems may then result in cool pre-explosion He stars.



Figure 8. Final outcome as a function of initial binary parameters using point-mass WD models (panel (a)) and, for selected systems (shown with blue edges), resolved WD models (panel (b)). Red boxes represent systems with central ignitions, boxes with black stripes show systems with off-center ignitions, and black boxes represent detached double WD binaries. In panel (b), dark (light) blue edges represent agreement (disagreement) in the final outcomes between the point-mass and resolved models.

#### 4.2. Resolved WD Binary Models

We re-simulate a portion of the point-mass grid, using a resolved WD model in order to account for off-center carbon ignitions self-consistently. For these models, we construct a 1.20  $M_{\odot}$  CO WD in MESA by scaling up the mass of a 1.00  $M_{\odot}$  CO WD. We evolve the binary until we identify one of the two following outcomes:

- 1. Off-center ignition. We identify the models with offcenter ignitions in the WD as those where energy release rate from carbon burning ( $\epsilon_{\rm CC}$ ) exceeds the non-nuclear neutrino cooling rate ( $\epsilon_{\nu}$ ) at an off-center temperature peak.
- 2. Central ignition. We identify the models with central ignitions in two ways. When central ignition of the WD occurs during stable accretion, we directly see  $\epsilon_{\rm CC} \ge \epsilon_{\nu}$  at the WD center during the calculation. For models where helium flashes begin following stable accretion, we stop the calculation after a few flashes. If the corresponding point-mass model indicates that the system will produce a near  $M_{\rm Ch}$  WD, then we also classify it as central ignition.

Panel (b) of Figure 8 summarizes the results. To facilitate comparison, models that agree with the outcome in panel (a) are shown with dark blue edges, while models that disagree are shown with light blue edges. Some of the models which we attempted to re-simulate failed due to computational difficulties associated with He flashes on the WD and so the outcome is indeterminate. These systems are masked by a white box in panel (b), resulting in pink boxes (for central ignitions) and light gray boxes with black stripes (for off-center ignitions).

In contrast to the method of Wang et al. (2017) as applied in panel (a), our resolved WD models in panel (b) show off-center carbon ignitions for long-period systems (log  $P_d^i \ge 0.2$ ). This is because for the long-period systems, the mass-transfer rate has decreased significantly by the time WD approaches  $M_{\rm Ch}$ , leading to  $|\dot{M}_{\rm He}|$  below the value of  $\dot{M}_{\rm cr}$ , and thus identification as central ignitions according to the criterion of Wang et al. (2017). However, earlier in the evolution, well before the WD



**Figure 9.** Mass-transfer histories of two systems with  $M_{WD}^i = 1.20 M_{\odot}$  and  $M_{He}^i = 1.1 M_{\odot}$ , at an initial orbital period of  $\log P_d^i = 1.0$ . In the point-mass models (dashed), the WD reaches  $M_{Ch}$ . The mass-transfer rate has declined significantly from peak, reaching  $\dot{M}_{WD} < \dot{M}_{cr}$ , and so the method of Wang et al. (2017) suggests a central ignition in the WD. However, in the resolved models, off-center ignition occurs early on. The difference between the mass-transfer histories in their region of overlap is due to the fact that the point-mass model uses a fitted version of  $\dot{M}_{up}$  which is  $\approx 10\%$  lower than one realized in the resolved model.

approaches  $M_{\rm Ch}$ , an off-center ignition already occurred during a phase with higher  $\dot{M}_{\rm He}$ .

This is demonstrated by the mass-transfer history in Figure 9. The mass transfer peaks above  $\dot{M}_{up}$ , and so the WD accretes at this roughly constant rate of  $\approx 4 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ . As found by Wang et al. (2017), a WD accreting at this constant rate (which is  $>\dot{M}_{cr}$ ) experiences an off-center ignition. Here, that happens after the WD has grown to  $M_{WD} \approx 1.25 M_{\odot}$ . However, if the evolution is allowed to continue (as in the point-mass calculation) the accretion rate falls. By the time the WD reaches 1.38  $M_{\odot}$ , the accretion rate has fallen below  $\dot{M}_{cr}$  and so the prescription of Wang et al. (2017)—which considers  $\dot{M}$  at only this final point—classifies this as a central ignition. Because the off-center ignition occurs after only accreting a relatively small amount of mass ( $\approx 0.05 M_{\odot}$ ), detecting its occurrence requires a prescription that accounts for the changing mass-transfer rate throughout the evolution.



Figure 10. Kiel diagram (panel (a)) and H-R diagram (panel (b)) for pre-explosion He star models with ultra-massive CO WDs. Unfilled symbols indicate central ignitions, while filled symbols indicate models that undergo off-center ignitions and will not explode as TN SNe. Other aspects are the same as in Figure 4.



Figure 11. Color-magnitude diagrams for indicated optical WFC3/UVIS filters for ultra-massive CO WD models. Unfilled symbols indicate central ignitions, while filled symbols indicate models that undergo off-center ignitions and will not explode as TN SNe. Error bars indicate the pre-explosion source observed for SN 2012Z by McCully et al. (2014).

#### 4.3. Results and Implications

We similarly run another set of resolved models starting with a 1.10  $M_{\odot}$  CO WD. Figure 10 places the models for both WD masses on the Kiel and H-R diagrams; Figure 11 shows them on color-magnitude diagrams. In each plot, the filled points indicate the models that we identify as undergoing off-center ignition, and hence not undergoing a TN SN, but that previous work would have identified as having done so. Eliminating the off-center ignitions serves to eliminate the coolest and most luminous He star companions.

The fact that our resolved 1.20  $M_{\odot}$  CO WD models in longperiod binaries undergo off-center ignitions has significant implications for our understanding the progenitor of SN 2012Z. If SN 2012Z-S1 is a He star–WD binary, then either (i) SN 2012Z originates from a long-period ( $\gtrsim$ 10 days) He star–WD binary where the initial WD is massive ( $M_{WD}^i \approx 1.2 M_{\odot}$ ) but not a CO WD (so possibly a hybrid CO/ONe WD or an ONe WD), or (ii) the pre-explosion optical light from the system is not dominated by the (unmodified) emission from the He star.

# 5. Discussion and Conclusions

In this work, we have further investigated the He star-CO WD progenitor channel for thermonuclear supernovae, with a particular focus on the predicted properties of the donor He star at the time the WD explodes. In Section 2, we describe an extension of the binary evolution calculations of Wong & Schwab (2019) that allowed us to generate a set of He star models at the time the WD explodes over a large range of initial binary parameters. In Section 3, we characterize the preexplosion properties of the donor stars. Using stellar atmosphere models, we demonstrated that the blackbody assumption is sufficient for characterizing the optical emission from these stars. We compared the optical emission from our models to the properties of the source observed in pre-explosion imaging of the Type Iax SN 2012Z. In agreement with past work, we found that binaries with normal ( $\leq 1.05 M_{\odot}$ ) CO WDs dramatically fail to reproduce these observations. In Section 4, we made models beginning with ultra-massive ( $\approx 1.2 M_{\odot}$ ) CO WDs. If the WD is approximated as a point mass, such models have been previously demonstrated to better match the properties of the 2012Z preexplosion imaging. However, our models, which resolved the internal structure of the CO WD accretor, show that such systems undergo off-center carbon ignition and thus are not expected to produce thermonuclear supernovae.

We therefore conclude that, under the assumption that the He star donor dominates the optical light of the system, our selfconsistent He star–CO WD binary models fail to reproduce the properties of the detected source in pre-explosion imaging of the host galaxy of SN 2012Z (McCully et al. 2014). The other Type Iax SN with similarly deep pre-explosion host observations is SN 2014dt (Foley et al. 2015). That case resulted in a non-detection, as did SN 2008ge (Foley et al. 2010), which has shallower limits, and so both are consistent with our models.

The motivation for invoking the Chandrasekhar-mass, He star donor channel for Type Iax SNe remains (e.g., Jha 2017). The presence of strong Ni emission in the late-time spectra (Foley et al. 2016) suggests the high density explosion characteristic of a near- $M_{\rm Ch}$  WD. Population synthesis studies have shown that the He star channel contributes to TN SNe with delay times  $\leq 100$  Myr (Wang et al. 2009a; Claevs et al. 2014), consistent with the typical delay time of  $\approx 60$  Myr of SNe Iax, inferred from their nearby stellar populations (Takaro et al. 2020). In this study, we classified of the final outcome based on the location of carbon ignition in the accreting WD. Open questions remain about the evolution beyond the phase of off-center carbon ignition in massive WDs (e.g., Wu & Wang 2019; Wu et al. 2020), so it is possible that further progress will revise our understanding of which systems can explode, thereby altering the predicted companion properties.

Additionally, the fact that these are binary systems with complex evolutionary histories is not fully addressed by only considering the He star. Both the WD and its accretion disk can also be luminous, though the expected high effective temperatures of this emission imply these sources are subdominant in the optical. Material has also likely been ejected into the circumstellar environment due to nonconservative mass transfer and He novae.<sup>12</sup> This may be able to modify the emission: significant circumstellar reddening from

carbon-rich ejecta has been invoked for the He nova V445 Pup, see Woudt et al. 2009). Developing a more detailed understanding of the combined influence of the binary and its environment will be an important avenue for future work.

This investigation of this progenitor channel will be aided by other complementary probes. The He star donor is Roche-lobe filling at the time of explosion and so material from its outer layers may be entrained due the impact of SN ejecta. Thus this He star donor scenario can also be constrained by limits on the inferred amount of He present in late-time spectra. Our models predict a remaining He envelope mass of  $M_{\text{He env}} \approx 0.06-0.55 M_{\odot}$ . Current theoretical models predict a stripped He mass  $\sim 10^{-2} M_{\odot}$ , assuming a typical He star radius of  $R_{\text{He}} \approx 0.5 \text{ R}_{\odot}$  (Liu et al. 2013), in tension with emerging observational limits of  $\lesssim 10^{-3} M_{\odot}$  (Magee et al. 2019) and  $\lesssim 10^{-2} M_{\odot}$  (Jacobson-Galán et al. 2019). However, a stripped mass of  $\approx 3 \times 10^{-4} M_{\odot}$  was found in the simulation of Zeng et al. (2020) who assumed a weak pure deflagration model. We also note that a limit of  $\lesssim 2 \times 10^{-3} M_{\odot}$  is found for stripped H in SNe Iax (Jacobson-Galán et al. 2019).

Nevertheless, even in the absence of significant stripping, the He star donor channel may provide an explanation for the detection of helium emission in the early-time spectra of SNe 2004cs and 2007J (Jacobson-Galán et al. 2019). In some systems of our simulated grid, the pre-explosion mass-transfer rate drops below the stable regime, such that the WD undergoes He novae and ejects He-rich material into the environment. This is consistent with the inference of the He emission to be originating from circumstellar He (Jacobson-Galán et al. 2019).

Searching for the surviving He star companion may offer another constraint on the He star donor channel. If the surviving companion is relatively unperturbed, a search in the UV may be useful, for nearby TN SNe (see our Figure 5). However, our pre-explosion He star models appear to be too blue for the post-explosion source found in SN 2008 ha (Foley et al. 2014) and in SN 2012Z (McCully et al. 2021). On the other hand, the simulations by Pan et al. (2013) show that the surviving companion brightens significantly, and may alter its colors, in a timescale in  $\approx 10-30$  yr. Their binaries are much more compact than ours, with their longest period binary at 3610 s (log  $P_d^f \approx -1.40$ ), so it is unclear how our He stars in wider binaries are impacted by the SN ejecta. Future simulations of He star-ejecta interaction in a long-period system, with various degrees of He envelope-stripping, may help shed light on this problem.

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<sup>&</sup>lt;sup>12</sup> In a recent study, Moriya et al. (2019) consider this environment and show the expected circumstellar density is consistent with the non-detection of radio emission in a number of observed events.



Figure 12. H-R diagrams for pre-explosion He star models with  $M_{WD}^i = 0.9-1.05 M_{\odot}$  CO WDs (panel (a)), and with  $M_{WD}^i = 1.1-1.2 M_{\odot}$  ultra-massive CO WDs (panel b), same as Figures 4 and 10 but with Kolb and tau\_factor=1 adopted for the models.

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Software: MESA (v10398; Paxton et al. 2011, 2013, 2015, 2018, 2019), ipython/jupyter (Pérez & Granger 2007; Kluyver et al. 2016), matplotlib (Hunter 2007), NumPy (van der Walt et al. 2011), and starkit (https://github.com/starkit/starkit), wsynphot (https://github.com/starkit/wsynphot), Python from python.org.

# Appendix Modeling the Donor Mass Transfer

During this work, we became aware that some of our He star models, particularly the long-period systems with  $M_{WD}^i = 0.90$ and 0.95  $M_{\odot}$ , have radii that exceed their Roche-lobe radii by up to factors of a few. We believe that this behavior is unphysical because the mass-transfer rate is expected to increase exponentially as the donor overfills its Roche lobe (e.g., Ritter 1988). The large overfill factors are seen when the He star starts to come out of contact and the envelope becomes highly radiation dominated. Under these conditions, us adopting tau factor=100 (i.e., the surface cell is placed at an optical depth of  $\tau = 100 \times 2/3$ ) appears to have an effect on the envelope structure. In this Appendix, we test the effects of adopting different physical assumptions, namely adopting the Kolb mass-transfer scheme (Kolb & Ritter 1990) which considers optically thick mass transfer, and setting tau\_factor=1 for the He star. With these two changes, we resimulated all the point-mass models shown in this work, with  $M_{\rm WD}^i$  ranging from 0.9–1.2  $M_{\odot}$ .

The resulting H-R diagrams for the pre-explosion He stars are shown in Figure 12. For  $M_{WD}^i = 0.9-1.05 M_{\odot}$  (panel (a)), adopting Kolb and tau\_factor=1 in general increases the mass retention efficiency, and allows a few more systems on the boundary of the TN SN region to reach  $M_{Ch}$ . It also keeps

the He star radii to within  $\approx 10\%$  of the Roche-lobe radii for systems in the TN SN region. As a result, the pre-explosion He stars have higher  $T_{\rm eff}$  compared with Figure 4, panel b. This change in  $T_{\rm eff}$  mainly affects the long-period systems in which the He star has nearly exhausted its envelope. We also note that the mass-transfer history near peak  $\dot{M}_{\rm He}$  is relatively unchanged. As expected, we only see a change in masstransfer history for the long-period systems as the donor starts to come out of contact.

Similarly, the mass-transfer histories show good agreement between the new tau\_factor=1 and the old tau\_factor=100 point-mass runs, for the  $M_{\rm WD}^i = 1.1 M_{\odot}$  models, and the  $M_{\rm WD}^i = 1.2 M_{\odot}$  models with log  $P_{\rm d}^i \leq 0.2$ -0.3. It is therefore not surprising that for these models, the TN SN regions obtained by applying the  $\dot{M}_{\rm cr}$  criterion of Wang et al. (2017) remain nearly unchanged.

However, the mass-transfer history starts to differ for  $M_{\rm WD}^i = 1.2 \, M_{\odot}$  and  $\log P_{\rm d}^i \gtrsim 0.3$  because of a surface convection zone that was not captured previously with tau\_factor=100. With longer  $\log P_{\rm d}^i$ , the surface convection zone encloses more mass and increasingly changes the behavior of  $\dot{M}_{\rm He}$  near peak. Peak  $\dot{M}_{\rm He}$  increases, so that the He star exhausts its envelope more easily. While the outcomes for  $M_{\rm WD}^i = 1.2 \, M_{\odot}$  and  $\log P_{\rm d}^i \leqslant 0.5$  remain unchanged, a discrepancy in outcome starts to arise for  $\log P_{\rm d}^i > 0.5$ , and in turn the TN SN boundary moves to shorter  $\log P_{\rm d}^i$ .

We do not re-simulate resolved models for  $M_{WD}^i = 1.1$  and  $1.2 M_{\odot}$ , and thus cannot identify with certitude systems that the  $\dot{M}_{cr}$  criterion of Wang et al. (2017) would misclassify as one that undergoes a central ignition. However, for  $M_{WD}^i = 1.1 M_{\odot}$ , and  $M_{WD}^i = 1.2 M_{\odot}$  with  $\log P_d^i \leq 0.2$ –0.3, given the good agreement in mass-transfer histories, we can still rely on our prior identification. Furthermore, our resolved  $M_{WD}^i = 1.2 M_{\odot}$  models invariably undergo off-center ignition if the WD is always accreting at  $\dot{M}_{WD} = \dot{M}_{up}$  until its mass grows to

 $M_{\rm WD} \approx 1.26 \, M_{\odot}$  (see also Figure 9). This is always the case for the systems with  $M_{\rm WD}^i = 1.2 \, M_{\odot}$  and  $\log P_{\rm d}^i \gtrsim 0.3$  that reach  $M_{\rm Ch}$ , so we can also reliably classify them as systems would undergo off-center ignition.

The H-R diagram for  $M_{WD}^i = 1.1$  and  $1.2 M_{\odot}$  is shown in in Figure 12, panel (b). Compared with Figure 10, panel (b), the locations of  $M_{WD}^i = 1.1$  systems show little change, and as do the  $M_{WD}^i = 1.2$  systems that we expect would experience a central ignition. The  $M_{WD}^i = 1.2$  systems that we expect would experience an off-center ignition are located at slightly higher  $T_{\text{eff}}$ , due to the change in mass-transfer history for  $\log P_{d}^i > 0.2$ –0.3.

Overall, these pre-explosion He star models with different assumptions about the mass transfer and the envelope of the He star show similar properties to the models we presented in the main body of this work. Therefore, our conclusions remain unchanged. However, this Appendix together with the necessity for us to use the MLT++ capacity of MESA serve to highlight the uncertainties associated with modeling mass transfer from a donor star with a highly radiation-dominated envelope, which remains a caveat of our work.

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