

THE HYBRID CONe WD + He STAR SCENARIO FOR THE PROGENITORS OF TYPE Ia SUPERNOVAE

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ABSTRACT

Hybrid CONe white dwarfs (WDs) have been suggested to be possible progenitors of type Ia supernovae (SNe Ia). In this Letter, we systematically studied the hybrid CONe WD + He star scenario for the progenitors of SNe Ia, in which a hybrid CONe WD increases its mass to the Chandrasekhar mass limit by accreting He-rich material from a non-degenerate He star. We obtained the SN Ia birthrates and delay times for this scenario using to a series of detailed binary population synthesis simulations. The SN Ia birthrates for this scenario are $\sim 0.033\text{--}0.539 \times 10^{-3} \text{ yr}^{-1}$, which roughly accounts for 1%–18% of all SNe Ia. The estimated delay times are $\sim 28 \text{ Myr--}178 \text{ Myr}$, which makes these the youngest SNe Ia predicted by any progenitor model so far. We suggest that SNe Ia from this scenario may provide an alternative explanation for type Iax SNe. We also presented some properties of the donors at the point when the WDs reach the Chandrasekhar mass. These properties may be a good starting point for investigating the surviving companions of SNe Ia and for constraining the progenitor scenario studied in this work.

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

Online-only material: color figures

1. INTRODUCTION

Type Ia supernovae (SNe Ia) have a prominent role in modern astrophysics and are the best standard candles for probing the universe on cosmological scales due to their high luminosities and remarkable uniformities (e.g., Riess et al. 1998; Perlmutter et al. 1999). However, the identity of their progenitors and the physics of their explosion mechanisms are still uncertain (see Hillebrandt & Niemeyer 2000; Podsiadlowski et al. 2008; Wang & Han 2012; Maoz et al. 2014).

SNe Ia are thought to be thermonuclear explosions of carbon–oxygen white dwarfs (CO WDs) at about the Chandrasekhar mass, although the means by which they grow to about the Chandrasekhar mass still remain unclear (see Nomoto et al. 1997). Two kinds of progenitor models have been proposed as possible mechanisms by which SNe Ia can be produced: single-degenerate and double-degenerate models. In the single-degenerate model, a CO WD can accrete H- or He-rich matter from a non-degenerate star to increase its mass to approach the Chandrasekhar mass, and then generate a thermonuclear explosion to become an SN Ia, in which the donor star could be a main sequence star, subgiant, red giant, or He star (e.g., Hachisu et al. 1996; Li & van den Heuvel 1997; Langer et al. 2000; Han & Podsiadlowski 2004; Meng et al. 2009; Wang et al. 2009a). In the double-degenerate model, SNe Ia arise from the merging of two CO WDs in a close binary. The closeness of the two WDs is due to common-envelope (CE) evolution, which then enables gravitational wave radiation to drive orbital inspiral to the merger (e.g., Webbink 1984; Iben & Tutukov 1984). Some variants of these two models have been proposed to explain the observed diversity of SNe Ia (for recent reviews, see Wang & Han 2012; Maoz et al. 2014).

According to hydrodynamic simulations, Denissenkov et al. (2013) recently suggested that convective boundary mixing in a super-asymptotic giant branch (AGB) star can prevent carbon

burning from reaching the center,⁴ and will lead to the formation of a hybrid CONe WD after the star has lost its envelope; such a WD has an unburnt CO core surrounded by a thick ONe zone. Following the work of Denissenkov et al. (2013), Chen et al. (2014) found that, considering the uncertainty of the carbon burning rate (CBR) and the treatment of convective boundaries, hybrid WDs may be produced even by stars with an initial mass $> 7.0 M_{\odot}$; the mass of these WDs could be close to $1.3 M_{\odot}$ in the extreme case of adopting a CBR factor of 0.1.⁵ It is easy for these hybrid WDs to grow to the Chandrasekhar mass limit by accreting matter, which could increase the birthrates of SNe Ia if CONe WDs can actually produce SNe Ia. Note that Denissenkov et al. (2014) recently found that hybrid WDs could reach a state of explosive carbon ignition, depending on the convective Urca process and some mixing assumptions.

Motivated by the work of Chen et al. (2014), Meng & Podsiadlowski (2014) recently investigated the CONe WD + MS scenario of SN Ia progenitors using a detailed binary population synthesis (BPS) method. However, a CONe WD can also accrete matter from a He star to increase its mass, and then explode as an SN Ia (this is referred to as the CONe WD + He star scenario in this work). The purpose of this Letter is to estimate the SN Ia birthrates and delay times in this scenario. The Letter is organized as follows. In Section 2, we describe our basic

⁴ Convective boundary mixing (CBM) flattens a carbon abundance profile below the formal boundary of the carbon convective shell defined by the Schwarzschild criterion, because the CBM transports carbon from there into the convective shell, where it is burned. For the carbon shell burning to steadily propagate to the center, the carbon abundance should be sufficiently high immediately below the Schwarzschild boundary, i.e., it should steeply increase with distance from the boundary. This condition is not fulfilled in the presence of the CBM. In other words, the CBM actually deprives the carbon shell burning of its fuel on its way to the center (see Denissenkov et al. 2013).

⁵ The fiducial carbon burning rate is a factor of 1.0 (see Caughlan & Fowler 1988). For more detailed discussions on the carbon burning rate, see Bennett et al. (2012) and Pignatari et al. (2013).

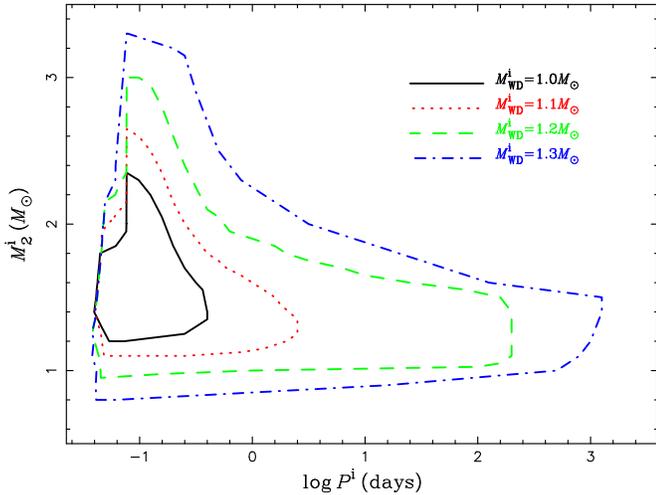


Figure 1. Contours in the initial orbital period and initial companion mass plane for CONe WD binaries that produce SNe Ia for various initial WD masses.

(A color version of this figure is available in the online journal.)

assumptions for numerical calculations. We present the results of our calculations in Section 3. Finally, a discussion and summary are given in Section 4.

2. NUMERICAL METHODS

In the CONe WD + He star scenario, a CONe WD accretes matter from a He star when it fills its Roche lobe. The donor star transfers some of its matter to the surface of the WD, which leads to the increase in the WD mass. If the WD grows up to $1.378 M_{\odot}$, we assume that it explodes as an SN Ia. Based on the optically thick wind model (Hachisu et al. 1996),⁶ Wang et al. (2009a) have already obtained a dense model grid leading to SNe Ia with solar metallicity for various initial WD masses except for $1.30 M_{\odot}$. Adopting the assumptions of Wang et al. (2009a), we obtained the initial parameter space leading to SNe Ia for $M_{\text{WD}}^i = 1.30 M_{\odot}$. Figure 1 presents the contours leading to SNe Ia for different initial WD masses.

In order to obtain SN Ia birthrates and delay times, a series of Monte Carlo simulations in the BPS approach are performed. For each BPS realization, we used Hurley’s rapid binary evolution code (Hurley et al. 2002) to follow the evolution of 4×10^7 sample binaries.⁷ Following the work of Meng & Podsiadlowski (2014), we also assumed that, if the mass of a WD is less than the most massive hybrid one shown in Figure 5 of Chen et al. (2014) and is not a CO WD, then it is a hybrid CONe WD. These binaries are followed from star formation to the formation of the CONe WD + He star systems based on three binary evolutionary channels (i.e., the *He star*, *EAGB*, and *TPAGB channels*; see Wang et al. 2009b). If the initial parameters of a CONe WD + He star system at the beginning of the Roche-lobe overflow (RLOF) are located in the SN Ia production regions in the plane of the initial orbital period and initial companion mass for its specific initial WD mass (Figure 1), then an SN Ia is assumed to be formed. The factors

⁶ The optically thick wind model is still controversial (see Langer et al. 2000).

⁷ We did not consider super winds in the evolution of the AGB star. If mass loss in the super wind is rapid enough, it can drive expansion of the binary orbit (and of the Roche lobe of the WD progenitor) faster than stellar evolution, preventing Roche-lobe overflow. This could reduce the SN Ia birthrates studied in this work.

Table 1
SN Ia Birthrates for Different BPS Simulation Sets,
in Which Set 2 is Our Standard Model

Set	$\alpha_{\text{ce}}\lambda$	CBR	IMF	$n(q)$	Rate (10^{-3} yr^{-1})
1	0.5	0.1	MS79	Constant	0.073
2	1.0	0.1	MS79	Constant	0.298
3	1.5	0.1	MS79	Constant	0.473
4	1.5	1	MS79	Constant	0.348
5	1.5	10	MS79	Constant	0.097
6	1.5	0.1	S86	Constant	0.269
7	1.5	0.1	MS79	Rising	0.539
8	1.5	0.1	MS79	Uncorrelated	0.033

of the CBR are set to 0.1, 1, and 10 based on Figure 5 in Chen et al. (2014).

We conduct eight sets of Monte Carlo simulations to examine their influence on the SN Ia birthrates, where we set the BPS parameters to a reasonable range (see Wang et al. 2009b). The details of the initial conditions of the BPS simulations are given in Table 1. A summary of the various given initial conditions is as follows. (1) Either it has a constant star formation rate (SFR) over the past 14 Gyrs or, alternatively, it is modeled as a delta function in the form of a single starburst. (2) The initial mass function (IMF) is from either Miller & Scalo (1979, MS79) or Scalo (1986, S86). (3) It has a mass-ratio distribution ($n(q)$) that is either constant, rising, or calculated from the case in which both binary components are chosen randomly and independently from the IMF (uncorrelated). (4) All stars are assumed to be members of binaries that have an initially circular orbit. (5) The distribution of initial orbital separations is assumed to be constant in $\log a$ for wide binary systems, in which a is the orbital separation (e.g., Han et al. 1995). (6) The standard equations describing energy are used to calculate the output during the cCE phase (e.g., Webbink 1984). Similar to our previous studies (e.g., Wang et al. 2009b), we use a single free parameter $\alpha_{\text{ce}}\lambda$ to describe the CE ejection process, and adopt three specific values (0.5, 1.0, and 1.5).

3. RESULTS

3.1. Distribution of Initial WD Masses

Figure 2 shows the distribution of the initial CONe WD masses of the WD + He star systems that ultimately produce SNe Ia with different values of $\alpha_{\text{ce}}\lambda$. This distribution is given at the current epoch by assuming an ongoing constant SFR. From this figure, we can see that a low value of $\alpha_{\text{ce}}\lambda$ tends to lead to higher initial WD masses. This trend can be understood using the He star channel as defined by Wang et al. (2009b), which allows a stable RLOF, leading to the formation of more massive WDs; a low value of $\alpha_{\text{ce}}\lambda$ in our BPS simulations will increase the fraction of SNe Ia that can be produced by the He star channel, and thus tend to form more massive WDs. However, we note that WD formation in the He star channel is different from the origin in super-AGB stars as described by Denissenkov et al. (2013); as such, it is unclear whether or not WDs from the He star channel may be hybrid CONe WDs, as we assume.

3.2. Birthrates and Delay Times of SNe Ia

According to the eight sets of simulations for the CONe WD + He star scenario, the estimated SN Ia birthrates are

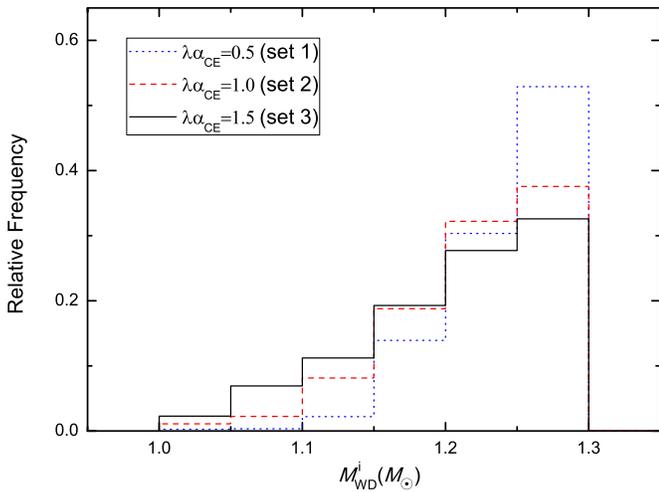


Figure 2. Distribution of the initial CONe WD masses that can ultimately produce SNe Ia with different values of $\alpha_{ce}\lambda$.

(A color version of this figure is available in the online journal.)

strongly dependent on the choice of the initial conditions; they are sensitive to the choice of the CE ejection parameter, CBR, IMF, and initial mass ratio distribution, etc. Notably, if we adopt an extreme mass-ratio distribution with uncorrelated component masses (set 8), the SN Ia birthrate will decrease significantly. This is because most of the donors in this scenario are not massive, the result of which is that WDs cannot accrete enough mass to grow to the Chandrasekhar mass.

In Figure 3, we compare the evolution of SN Ia birthrates for a constant SFR ($3.5 M_{\odot} \text{ yr}^{-1}$; left panel) and a single starburst (right panel). According to our standard model (set 2), the SN Ia birthrates are $\sim 0.298 \times 10^{-3} \text{ yr}^{-1}$, which is roughly one-tenth of the observed birthrate ($\sim 3 \times 10^{-3} \text{ yr}^{-1}$; Cappellaro & Turatto 1997). Even the largest birthrate in our BPS model (set 7) is only a factor of two greater. This indicates that the CONe WD + He star scenario can only be responsible for part of the total SN Ia birthrate (for other SN Ia formation scenarios, see Wang & Han 2012). We note that SN Ia birthrates will become lower with the decrease in $\alpha_{ce}\lambda$ (see the left panel). This is because more binaries after the CE ejection may merge with a low $\alpha_{ce}\lambda$. In

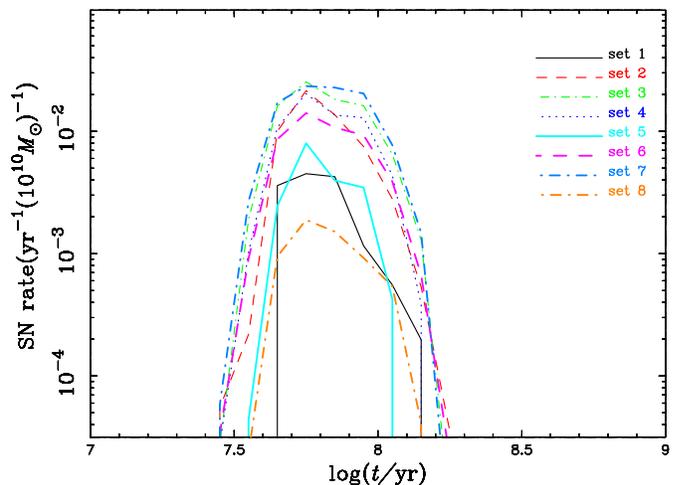
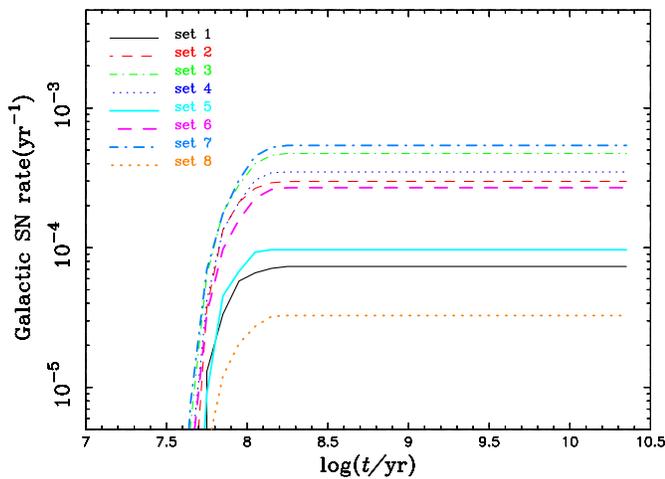


Figure 3. Left panel: the evolution of SN Ia birthrates for a constant SFR with different BPS simulation sets. Right panel: similar to the left panel, but for a single starburst.

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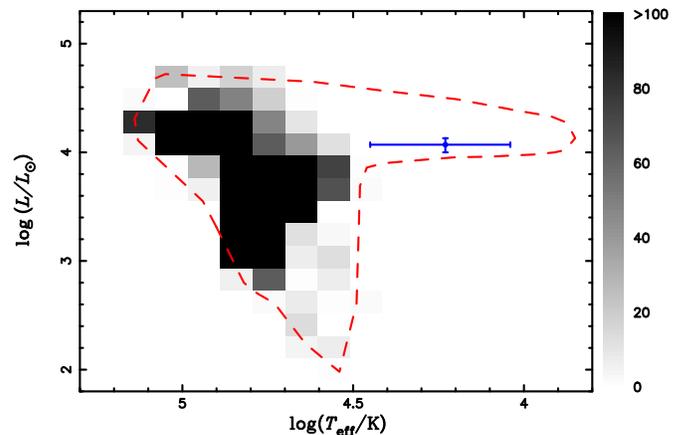


Figure 4. Distribution of properties of the donors in the plane of $(\log T_{\text{eff}}, \log L)$ when the WDs grow to $1.378 M_{\odot}$. Here, we set $\alpha_{ce}\lambda = 1.5$ (set 3). The dashed line denotes the final region obtained from the binary calculations in Figure 1. The error bars present the location of the possible companion in the SN 2012Z progenitor system, the luminosity and temperature of which are based on a blackbody approximation of the measurements of McCully et al. (2014).

(A color version of this figure is available in the online journal.)

addition, the SN Ia birthrates decrease with the CBR factor; a high CBR factor will result in a small upper mass limit for the CONe WDs, and consequently a low birthrate.

In Figure 3, we also present the delay time distributions of SNe Ia obtained from a single starburst (see the right panel). From this panel, we see that SN Ia explosions occur between ~ 28 Myr and ~ 178 Myr after the starburst, which may contribute to the population of young SNe Ia in late-type galaxies. Wang et al. (2009b) found that the minimum delay time from the CO WD + He star scenario is ~ 45 Myr, which is longer than the results obtained in this work. It seems that SNe Ia from the CONe WD + He star scenario are the youngest of all current progenitor models.

3.3. Surviving Companions of SNe Ia

The donor star in the CONe WD + He star scenario would survive and potentially be identifiable if the WD was completely disrupted at the moment of the SN explosion (e.g., Wang & Han 2009; Pan et al. 2010; Liu et al. 2013). By interpolating in

the three-dimensional grid (initial WD mass, initial companion mass, and initial orbital period) of the WD + He star systems (Figure 1), we can obtain many properties of the companions when the WDs grow to $1.378 M_{\odot}$, e.g., the luminosities, effective temperatures, orbital velocities, and surface abundances. These properties may be observed and be used to help identify the companions. Figure 4 shows an example of the distributions of the properties of companions in the plane of the effective temperature and luminosity at the point when the WD increases its mass to $1.378 M_{\odot}$, which may be helpful in identifying the surviving companions. In this figure, we also present the final region obtained from the binary calculations in Figure 1 (see the dashed line). The possible He companion star in the SN 2012Z progenitor system is located in this region (for a discussion, see Section 4).

4. DISCUSSION AND CONCLUSIONS

SNe Ia from the CONe WD + He star scenario may exhibit some special properties. In this scenario, the WD accretes material from a non-degenerate He star, which could result in the detection of He lines in the early spectra of such SNe Ia. In addition, SNe Ia from this scenario are relatively young and have delay times as short as ~ 28 Myr; such SNe Ia may be detected in galaxies with recent star formation. Some previous works indicate that the SN Ia luminosities at maximum could be mainly dependent on the carbon abundance, i.e., a low carbon abundance leads to a smaller amount of ^{56}Ni synthesized in the thermonuclear explosion, which results in a lower peak luminosity of SNe Ia (e.g., Umeda et al. 1999). Compared with normal CO WDs, hybrid WDs have a relatively low carbon abundance (e.g., Denissenkov et al. 2014). Therefore, SNe Ia from these hybrid WDs could be expected to have a lower peak luminosity and a lower explosion energy (a relatively low ejecta velocity could thus be expected).

It has recently been proposed that one subclass of SNe Ia is so distinct as to be classified separately from the bulk of SNe Ia, with a suggested name of type Iax SNe (SNe Iax), which contain SNe resembling the prototype event SN 2002cx (e.g., Foley et al. 2013). This type of SN may be an excellent candidate to be observational counterparts of SNe Ia via the CONe WD + He star scenario. SNe Iax have maximum luminosities as low as that of the faint 1991bg-like events, and have lower maximum-light velocities compared with normal ones, but they show iron-rich spectra at maximum light like the bright 1991T-like objects (Foley et al. 2013). So far, about 25 SNe Iax have been identified, in which two of them show strong He lines in their spectra,⁸ and most of them have been discovered in late-type galaxies (Foley et al. 2013). Lyman et al. (2013) found that the host population of SNe Iax is very young, which is comparable to that of type IIp SNe, and thus suggested that SNe Iax may have a delay time of 30–50 Myr. Foley et al. (2014) recently constrained the progenitor system of SN 2008ha to have an age of < 80 Myr. The estimated birthrates of SNe Iax may account for 5%–30% of the overall SN Ia birthrate (e.g., Li et al. 2011; Foley et al. 2013; White et al. 2014). The above observed properties of SNe Iax seem comparable to those from the CONe WD + He star scenario.

McCully et al. (2014) recently found that one SN Iax (i.e., SN 2012Z) was probably an explosion of a WD accreting matter from a He star. In Figure 4, we can see that the

possible He companion star is a little cooler than our BPS results, but this is merely a selection effect due to the initial conditions of the populations we consider in our BPS studies; it still lies in the region that can potentially be reached by our binary simulations. The long-period systems in Figure 1 should contribute significantly to the number of systems in the vicinity of SN 2012Z, even though it is difficult for our current BPS approach to reflect this. Thus, we cannot exclude the He donor star as a probable companion of SN 2012Z.

However, the CONe WD + He star scenario cannot explain one particular SN Iax, i.e., SN 2008ge, which was discovered in an old environment, hosted by an S0 galaxy with no massive stars or any sign of star formation (Foley et al. 2010). This indicates that SNe Iax have a heterogeneous class of progenitors. We note that some other models have already been proposed to produce SNe Iax, e.g., a failed deflagration model of a Chandrasekhar mass WD (e.g., Jordan et al. 2012; Kromer et al. 2013; Long et al. 2014), a specific class of He-ignited WD explosions (Wang et al. 2013), and the CONe WD + MS scenario (Meng & Podsiadlowski 2014).

Observationally, some massive WD + He star binaries (e.g., HD 49798 with its WD companion and V445 Pup) are candidates of SN Ia progenitors. (1) HD 49798 is a H-depleted subdwarf O6 star that contains a massive WD companion with an orbital period of 1.548 d (e.g., Bisscheroux et al. 1997). Mereghetti et al. (2009) obtained the masses of these two components, in which the WD mass is $1.28 \pm 0.05 M_{\odot}$ and the He star mass is $1.50 \pm 0.05 M_{\odot}$. (2) V445 Pup is a He nova. The light curve fitting by Kato et al. (2008) shows that the WD mass is $\gtrsim 1.35 M_{\odot}$. Woudt et al. (2009) deduced that the pre-outburst luminosity of the system was $\log(L/L_{\odot}) = 4.34 \pm 0.36$, which is compatible with a 1.2–1.3 M_{\odot} He star that is burning its He shell (see also Piersanti et al. 2014). Goranskij et al. (2010) recently reported that the most probable orbital period for this binary is ~ 0.65 d. The parameters of these two binaries are located in the initial parameter space contours for producing SNe Ia (see Figure 1). Thus, they are possible progenitor candidates of SNe Ia. However, it is still uncertain which type of WDs are in these two binaries, e.g., CO WDs, CONe WDs, or ONE WDs. If they are CONe WDs, they could form SNe Ia through the scenario studied in this work.

Using a detailed BPS approach and assuming CONe WDs can produce SNe Ia, we systematically investigated the hybrid CONe WD + He star scenario for the progenitors of SNe Ia. We obtain the birthrates and delay times for this scenario. The birthrate from this scenario could account for 1%–18% of the total SNe Ia, the specific proportion of which is strongly sensitive to uncertainties in some input parameters for the Monte Carlo simulations. SNe Ia from this scenario could be as young as ~ 28 Myr, which would be the youngest SNe Ia ever modeled. We found that SNe Ia from this scenario will exhibit some special properties when compared with normal ones, and may explain some SNe Iax. We also provided the properties of donors when the WD mass increases to $1.378 M_{\odot}$. These properties are a starting point for investigating the surviving companions of SNe Ia. In order to set further constraints on the hybrid CONe WD + He star scenario, large samples of massive WD + He star systems and surviving companions are needed. We hope that our work stimulates numerical simulations on thermonuclear explosions of hybrid CONe WDs.

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⁸ Foley et al. (2013) speculated that all SNe Iax may have significant amounts of He in their ejecta.

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