

## Research Article

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# The WD+He star binaries as the progenitors of type Ia supernovae

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**Abstract:** Employing the MESA stellar evolution code, we computed He accretion onto carbon-oxygen white dwarfs (CO WDs). We found two possible outcomes for models in which the WD steadily grows in mass towards the Chandrasekhar limit. For relatively low He-accretion rates carbon ignition occurs in the center, leading to a type Ia supernova (SN Ia) explosion, whereas for relatively high accretion rates carbon is ignited off-center, probably leading to collapse. Thus the parameter space producing SNe Ia is reduced compared to what was assumed in earlier papers, in which the possibility of off-center ignition was ignored. We then applied these results in binary population synthesis modelling, finding a modest reduction in the expected birthrate of SNe Ia resulting from the WD+He star channel.

**Keywords:** white dwarfs, binaries: close, stars: evolution

## 1 Introduction

The progenitor issue of type Ia supernovae (SNe Ia) is still under debate (see, e.g. Podsiadlowski et al. 2008; Wang & Han 2012). The single-degenerate (SD) model is one of the classical models for the production of SNe Ia. In this model, a carbon-oxygen white dwarf (CO WD) can accrete H-rich material from a main-sequence star or a red-giant star to grow in mass to the Chandrasekhar limit and then form an SN Ia. Meanwhile, a CO WD in the SD model can also accrete He-rich material from a He star and then produce an SN Ia, which is called the WD+He star channel (e.g. Wang et al. 2009a,b). It has been suggested that the WD+He star channel is a noteworthy way to produce the observed young SNe Ia (e.g. Yoon & Langer 2003; Wang et al. 2009a,b). Meanwhile, many observed WD+He star systems have been proposed as the progenitor candidates of SNe Ia, e.g. HD 49798 with its WD companion, V445 Puppis, KPD 1930+2752, CD-30° 11223, etc.

However, the process of accreting He-rich material onto WDs is still not clearly understood. It has been suggested that the accretion rate plays a crucial role in the

evolution of He-accreting WDs (e.g. Nomoto 1982). If the accretion rate is too low, He-shell flashes will occur on the surface of the WD; if the accretion rate is too high, it will form a red-giant-like star. Therefore, helium can only be burnt into carbon and oxygen steadily in a narrow He-shell burning regime. Previous studies usually assumed that a WD can increase its mass to the Chandrasekhar limit in the stable He-shell burning regime and then form an SN Ia (e.g. Nomoto 1982). However, in this work we found that the He-accreting WD will experience center or off-center carbon ignition after long term evolution when the WD grows in mass close to the Chandrasekhar limit. The off-center carbon burning will change CO WDs into ONe WDs but not SNe Ia (e.g. Nomoto & Iben 1985; Saio & Nomoto 1985; Brooks et al. 2016), which may influence the birthrates of SNe Ia through the WD+He star channel.

In this work, we will simulate the long term evolution of the He accretion onto CO WDs by considering their structure equations. The accreted He-rich material consists of 2% metallicity and 98% He. The initial models of WDs in our simulations have masses in the range of  $0.6-1.35 M_{\odot}$  with metallicity  $Z = 0.02$ . A series of computations about the He accretion onto WDs are carried out with various accretion rates  $\dot{M}_{\text{acc}} = 10^{-8}-10^{-5} M_{\odot} \text{ yr}^{-1}$ . In order to get more detailed results about the accreting WDs, we resolve the WDs into more than 2000 mass shells.

This paper is organized as follows. The basic assumptions and methods for numerical calculations are given in Section 2. We give the numerical results in Section 3. In Section 4, we present the initial parameter spaces of the

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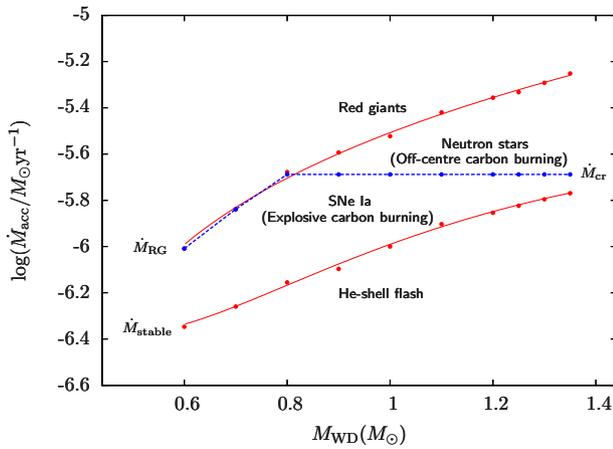
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WD+He star channel and the corresponding binary population synthesis results. Finally, a discussion is provided in Section 5.

## 2 Numerical code and methods

By employing the stellar evolution code named modules for experiments in stellar astrophysics (MESA; see Paxton et al. 2015), we computed the long-term evolution of the He accretion onto CO WDs with various accretion rates. The nuclear reaction network `co_burn.net` is used in our computations. Two MESA suite cases are adopted to perform our computations: `make_co_wd` and `wd2`. The suite case `make_co_wd` is adopted to build initial CO WD models, whereas the suite case `wd2` is used to compute the He accretion onto WDs. The suite case `wd2` includes an acceleration term in the equation of hydrostatic equilibrium, so we can simulate the mass ejection processes during He-shell flashes.

## 3 Numerical Results



**Figure 1.** Properties of the He-shell burning on the surface of the WDs in the plane of WD mass and accretion rate. The blue dotted line is a critical accretion rate  $\dot{M}_{cr}$ , above which off-center carbon burning happens. The red solid lines are the fitting for the values of  $\dot{M}_{stable}$  and  $\dot{M}_{RG}$ .

We carried out a series of computations with WD masses of  $0.6\text{--}1.35 M_{\odot}$  and with various accretion rates. Figure 1 presents the stable He-shell burning regime, where the WD can increase its mass steadily. If  $\dot{M}_{acc}$  is below the minimum accretion rate  $\dot{M}_{stable}$  for stable He-shell

burning, He-shell flashes will occur on the surface of the WD. If  $\dot{M}_{acc}$  is larger than the critical accretion rate  $\dot{M}_{RG}$  for stable He-shell burning, the WD will form a red-giant-like star. The values of  $\dot{M}_{stable}$  and  $\dot{M}_{RG}$  are approximated by the following algebraic form

$$\dot{M}_{stable} = 1.46 \times 10^{-6} \left( -M_{WD}^3 + 3.45M_{WD}^2 - 2.60M_{WD} + 0.85 \right), \quad (1)$$

$$\dot{M}_{RG} = 2.17 \times 10^{-6} (M_{WD}^2 + 0.82M_{WD} - 0.38), \quad (2)$$

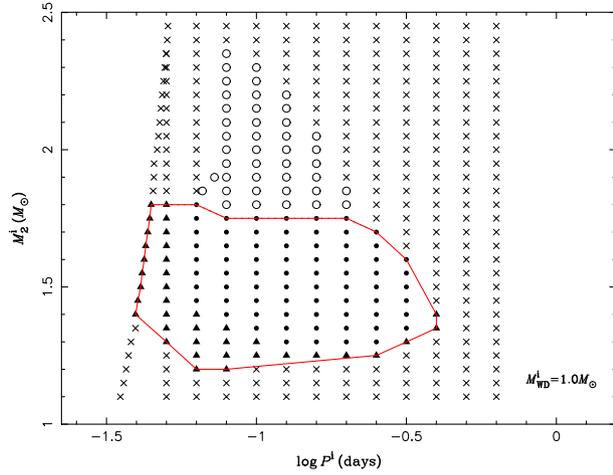
in which  $M_{WD}$  is in units of  $M_{\odot}$ , and  $\dot{M}_{stable}$  and  $\dot{M}_{RG}$  are in units of  $M_{\odot} \text{ yr}^{-1}$ .

It has been assumed that a WD can increase its mass to the Chandrasekhar limit in the stable He-shell burning regime and then form an SN Ia (e.g. Nomoto 1982). However, in this work we found two possible outcomes for models in which the WD steadily grows in mass towards the Chandrasekhar limit. If  $\dot{M}_{acc}$  is above a critical value  $\dot{M}_{cr}$  ( $\sim 2.05 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ ), off-center carbon ignition happens on the surface of the WD. An off-center carbon ignition may convert CO WDs to ONe WDs, resulting in accretion induced collapse rather than an SN Ia (e.g. Saio & Nomoto 1985; Nomoto & Iben 1985). The WD can grow in mass steadily in the regime between  $\dot{M}_{cr}$  and  $\dot{M}_{stable}$ , where explosive carbon ignition can happen in the center of the WD. The WD will be destroyed by the explosive carbon burning, leading to SN Ia explosions (see also Chen et al. 2014).

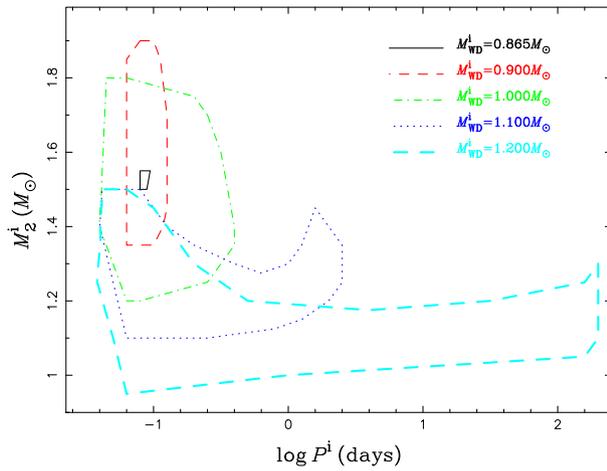
## 4 The WD+He star channel

### 4.1 Initial parameter for SNe Ia

In order to determine the initial parameter of WD+He star binaries that can lead to SNe Ia, Wang et al. (2009a) performed a systematic study for the WD+He star channel with the Eggleton stellar evolution code (e.g. Eggleton 1973). According to a detailed binary population synthesis approach, Wang et al. (2009b) got the birthrates of SNe Ia for the WD+He star channel based on the initial parameter spaces for producing SNe Ia. However, Wang et al. (2009a) ignored the possibility of non-explosive off-center carbon ignition. The effect of including this possibility will shrink the initial parameter spaces for producing SNe Ia in the orbital period–secondary mass plane, and decrease the theoretical SN Ia birthrates. Here, we re-used the mass-transfer histories from Wang et al. (2009a) and then assume that off-center carbon burning happens if the mass-transfer rate is higher than  $\dot{M}_{cr}$  when the WD approaches the Chandrasekhar limit.



**Figure 2.** Estimated parameter spaces in the initial orbital period–secondary mass plane for an initial WD mass of  $1.0 M_{\odot}$ . The filled symbols are for those resulting in SN Ia explosions, *i.e.* the filled triangles and circles denote that the WD explodes in the weak He-shell flash phase and in the stable He-shell burning phase, respectively. Crosses implies systems that may form He novae that prevent the WD from reaching the Chandrasekhar mass limit, whereas open circles are those under off-center carbon burning. Source: From Wang et al. (2017).

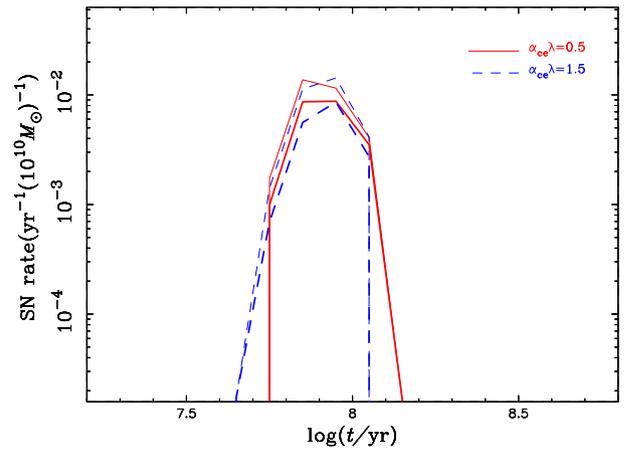


**Figure 3.** Initial contours in the orbital period–secondary mass plane for WD+He star binaries that can form SNe Ia with various WD masses. Source: From Wang et al. (2017).

Figure 2 presents the final results of the binary evolution computations in the initial orbital period–secondary mass plane for an initial WD mass of  $1.0 M_{\odot}$ , where the filled symbols are for those leading to SN Ia explosions. The filled triangles and circles denote that the WD explodes in the weak He-shell flash phase and in the stable He-shell burning phase, respectively. Some WD+He star systems fail to produce SNe Ia due to nova outbursts that prevent the WDs growing in mass (the crosses in this fig-

ure). The open circles are those under off-center carbon ignition that can form SNe Ia in Wang et al. (2009a). Figure 3 shows the initial contours of parameters for producing SNe Ia in the initial orbital period–secondary mass plane for various WD masses (*i.e.*  $M_{\text{WD}}^i = 0.865, 0.90, 1.0, 1.1$  and  $1.2 M_{\odot}$ ). The contour almost disappears for  $M_{\text{WD}}^i = 0.865 M_{\odot}$  which is supposed to be the minimum mass of the WD for the production of SNe Ia via the WD+He star channel.

## 4.2 Birthrates of SNe Ia



**Figure 4.** The birthrates of SNe Ia obtained from a single starburst of  $10^{10} M_{\odot}$ .

In order to investigate the birthrates of SNe Ia for the WD+He star channel, a series of Monte Carlo binary population synthesis computations are performed based on the Hurley rapid binary evolution code (*e.g.* Hurley et al. 2002). In each simulation, we follow the evolution of  $4 \times 10^7$  sample binaries from the primordial binaries to the production of the WD+He star binaries based on three binary evolutionary ways (*i.e.* the He star channel, the EAGB channel and the TPAGB channel). If the initial parameters of a CO WD+He star system are located in the SN Ia production contours in the initial orbital period–secondary mass plane for its specific  $M_{\text{WD}}^i$ , then an SN Ia is supposed to be produced. The standard energy equations are adopted to calculate the output during the common-envelope (CE) evolution. Similar to the previous work by Wang et al. (2009b), we also use a single free parameter  $\alpha_{\text{ce}}\lambda$  to calculate the CE ejection, and use two specific values (0.5 and 1.5).

By using metallicity  $Z = 0.02$  and a star-formation rate of  $5 M_{\odot} \text{yr}^{-1}$ , we obtain an SN Ia birthrate of  $\sim 0.2 \times 10^{-3} \text{yr}^{-1}$  in our galaxy based on the initial contours in Figure 3. This birthrate is lower than that of observations (*i.e.*  $3 \times 10^{-3} \text{yr}^{-1}$ ), which indicates that the WD+He star channel only produces a small part of all SNe Ia ( $\sim 7\%$ ). Figure 4 presents the birthrates of SNe Ia based on a single starburst with a total mass of  $10^{10} M_{\odot}$ . From this figure, we can see that SN Ia explosions from the WD+He star channel happen between  $\sim 45$ – $140$  Myr after the starburst, which may contribute to the observed SNe Ia in the young stellar population. SNe Ia in the young stellar population may have an influence on the current galactic chemical evolution models as they may feedback iron into their host galaxies much earlier than previously thought. The minimum delay time in Figure 4 is determined by the MS lifetime of a  $8 M_{\odot}$  star, which is the maximum mass of a star able to form CO WDs.

## 5 Discussion

Brooks et al. (2016) recently also reported these two possible outcomes (*i.e.*, centre or off-centre carbon ignition), but they calculated over a narrower range of parameter space. In the present work, we studied this question in a systematic way. Brooks et al. (2016) calculated full binary evolution of WD+He star systems, whereas we suppose that off-centre carbon burning occurs if the mass-transfer rate is higher than  $\dot{M}_{\text{cr}}$ . Note that the results obtained here are very similar to those of Brooks et al. (2016).

In addition, the classical double-degenerate model of SNe Ia, involving the merging of two CO WDs, is challenged by an off-center carbon burning owing to a high accretion rate during merging, which will convert CO WDs to ONe WDs and then collapse into neutron stars (*e.g.* Saio & Nomoto 1985; Nomoto & Iben 1985). It has been suggested that the critical accretion rate for off-center carbon ignition is  $\sim 2 \times 10^{-6} M_{\odot} \text{yr}^{-1}$  in the double-degenerate model (see Saio & Nomoto 1985). The critical accretion rate in the present work is  $\sim 2.05 \times 10^{-6} M_{\odot} \text{yr}^{-1}$  when an off-center carbon burning happens. By considering the possibility of the off-center carbon burning, the Galactic SN Ia birthrates from the WD+He star channel decrease to  $\sim 0.2 \times 10^{-3} \text{yr}^{-1}$ . Meanwhile, these off-center carbon burning provides a way to form neutron stars, which will increase the birthrates of accretion induced collapse events (see Brooks et al. 2017).

This work only studied the He-shell burning on the surface of the WD. However, in the single-degenerate

model a WD can also obtain H-rich material from its non-degenerate donor, which refers to the double-shell (H and He) burning. During the double-shell burning, the H-rich material is firstly burnt into He and then converted into carbon and oxygen, which increases the mass of the WD. However, stable H and He burning require different mass growth rates, so it is still difficult for the WD to grow in mass to the Chandrasekhar limit through the double-shell burning.

Using the MESA stellar evolution code, we performed a series of computations about the long term evolution of He-accreting CO WDs. We found that the accreting WDs will experience off-center or center carbon ignition when the WDs increase their masses close to the Chandrasekhar limit. Importantly, this work implies that a WD can increase its mass to the Chandrasekhar limit through the steady He accretion and form an SN Ia finally.

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