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He-accreting carbon–oxygen white dwarfs and Type Ia supernovae

Bo Wang,[1,2★] Philipp Podsiadlowski[3] and Zhanwen Han[1,2]
[1]*Key Laboratory for the Structure and Evolution of Celestial Objects, Yunnan Observatories, CAS, Kunming 650216, China*
[2]*Center for Astronomical Mega-Science, CAS, Beijing 100012, China*
[3]*Department of Astronomy, Oxford University, Oxford OX1 3RH, UK*

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ABSTRACT

He accretion on to carbon–oxygen white dwarfs (CO WDs) plays a fundamental role when studying the formation of Type Ia supernovae (SNe Ia). Employing the MESA stellar evolution code, we calculated the long-term evolution of He-accreting CO WDs. Previous studies usually supposed that a WD can grow in mass to the Chandrasekhar limit in the stable He burning region and finally produce an SN Ia. However, in this study, we find that off-centre carbon ignition occurs in the stable He burning region if the accretion rate is above a critical value ($\sim 2.05 \times 10^{-6}\,\mathrm{M_{\odot}\,yr^{-1}}$), resulting in accretion-induced collapse rather than an SN Ia. If the accretion rate is below the critical value, explosive carbon ignition will eventually happen in the centre producing an SN Ia. Taking into account the possibility of off-centre carbon ignition, we have re-determined the initial parameter space that produces SNe Ia in the He star donor channel, one of the promising channels to produce SNe Ia in young populations. Since this parameter space is smaller than was found in the previous study of Wang et al. (2009), the SN Ia rates are also correspondingly smaller. We also determined the chemical abundance profile of the He-accreting WDs at the moment of explosive carbon ignition, which can be used as initial input for SN Ia explosion models.

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

1 INTRODUCTION

Type Ia supernovae (SNe Ia) play an important role in cosmology and in our current understanding of the chemical evolution of galaxies (e.g. Matteucci & Greggio 1986; Howell 2011; Meng, Gao & Han 2015). There is some consensus that SNe Ia arise from thermonuclear explosions of carbon–oxygen white dwarfs (CO WDs) in binaries, although the mass donor is still uncertain (e.g. Hoyle & Fowler 1960; Nomoto, Iwamoto & Kishimoto 1997; Podsiadlowski et al. 2008). The mass donor could be a non-degenerate star in the single-degenerate (SD) model or another WD in the double-degenerate (DD) model (e.g. Whelan & Iben 1973; Iben & Tutukov 1984; Webbink 1984). For recent reviews on the progenitor issue of SNe Ia see, for example, Wang & Han (2012), Höflich et al. (2013), Hillebrandt et al. (2013), Ruiz-Lapuente (2014) and Maoz, Mannucci & Nelemans (2014).

In the classical SD model, a WD accretes H-rich matter from a MS star or a RG star (e.g. Hachisu, Kato & Nomoto 1996; Li & van den Heuvel 1997; Langer et al. 2000; Han & Podsiadlowski 2004, 2006; Wang, Li & Han 2010; Meng & Podsiadlowski 2017). It is also possible that a WD accretes He-rich matter from a He star or a He subgiant to grow in mass to the Chandrasekhar limit and then produce an SN Ia, which is referred to as the He star donor channel (see Yoon & Langer 2003; Wang et al. 2009a,b). It has been suggested that the He star donor channel is a particularly favourable channel for producing observed SNe Ia with short delay times (e.g. Mannucci, Della Valle & Panagia 2006; Cooper, Newman & Yan 2009; Ruiter et al. 2009; Wang et al. 2009a,b; Thomson & Chary 2011). Many recent binary population synthesis (BPS) studies also involved the He star donor channel (e.g. Ruiter et al. 2013, 2014; Claeys et al. 2014; Toonen et al. 2014).

Observationally, many WD+He star systems have been considered as progenitor candidates for SNe Ia, for example, V445 Puppis (see Kato et al. 2008; Woudt et al. 2009), HD 49798 with its WD companion (see Wang & Han 2010a; Mereghetti et al. 2011; Liu et al. 2015), CD −30° 11223 (see Vennes et al. 2012; Geier et al. 2013; Wang, Justham & Han 2013), KPD 1930+2752 (see Maxted, Marsh & North 2000; Geier et al. 2007), etc. Especially, V445 Puppis is a strong candidate for an SN Ia progenitor as the WD mass is at least 1.35 $\mathrm{M_{\odot}}$ and the mass retention efficiency of He accretion on to the WD appears to be as high as 50 per cent during nova outbursts (e.g. Kato et al. 2008). In addition, SN 2014J may originate from a WD+He star system, and the mass donor for the progenitor of SN 2012Z may have been a He star (e.g. Diehl et al. 2014; McCully et al. 2014; Wang et al. 2014a). Moreover, the hypervelocity He star US 708 and its spectroscopic twin J2050 could be surviving mass donors of SNe Ia that occurred in WD+He

★ E-mail: wangbo@ynao.ac.cn

star systems (e.g. Justham et al. 2009; Wang & Han 2009; Geier et al. 2015; Ziegerer et al. 2017). Note that WD+He star systems are also involved in the formation of some peculiar types of systems, such as AM CVn binaries (e.g. Nelemans et al. 2001; Brooks et al. 2015; Piersanti, Tornambé & Yungelson 2015) and double CO WDs (e.g. Ruiter et al. 2013; Liu et al. 2016).

However, the accretion of He-rich matter on to WDs is still not completely understood. Previous studies indicated that the accretion rate plays a crucial role in the evolution of the He-accreting WDs (e.g. Kato & Hachisu 2004; Piersanti, Tornambé & Yungelson 2014; Wang et al. 2015; Wu et al. 2016). If the accretion rate is too high, the WD will develop into a red-giant-like He star due to the continuous pileup of the accreted He-rich matter on its surface; if the accretion rate is too low, it will experience He-shell flashes due to unstable nuclear burning (e.g. Nomoto 1982a; Kato & Hachisu 2004; Wu et al. 2017). Previous studies usually assumed that a WD can grow steadily in mass to the Chandrasekhar limit in a narrow parameter region for stable He burning and then produce an SN Ia (e.g. Nomoto 1982a; Wang et al. 2009a). In contrast, in the present work where we followed the long-term evolution of the accreting WDs, we found that they can experience either centre or off-centre carbon ignition when their mass is close to the Chandrasekhar limit. Off-centre carbon burning will convert CO WDs into ONe WDs, ultimately leading to the formation of neutron stars rather than SNe Ia (e.g. Nomoto & Iben 1985; Saio & Nomoto 1985, 1998; Schwab, Quataert & Kasen 2016). This should affect the SN Ia rates in the He star donor channel, which will be studied in this work. Note that Brooks et al. (2016) recently also reported these two possible outcomes, but they considered only a narrow binary parameter space. Here, we explore this question in a systematic way and apply the results using a detailed BPS approach.

In most previous studies of the SD model, the WDs are taken as point masses, and their structure is not calculated when simulating mass accretion; the WDs are supposed to explode as SNe Ia once they have grown in mass to the Chandrasekhar limit (e.g. Lü et al. 2009; Meng & Yang 2012; Toonen et al. 2012; Bours, Toonen & Nelemans 2013). In this study, however, we calculate the long-term evolution of the He-accreting CO WDs by solving their structure equations. In Section 2, we introduce the basic assumptions and methods for the numerical simulations. The numerical results of our simulations are given in Section 3. In Section 4, we show the initial parameter space for SNe Ia based on the He star donor channel and the corresponding BPS results. Finally, we discuss the results in Section 5 and give a summary in Section 6.

2 NUMERICAL METHOD

2.1 Stellar evolution code

Using the MESA stellar evolution code (version 7624; see Paxton et al. 2011, 2013, 2015), we calculate the long-term evolution of He-accreting CO WDs. The default OPAL opacity is used in our simulations, and the nuclear reaction network `co_burn.net` is adopted. This nuclear reaction network contains isotopes needed for helium, carbon and oxygen burning, which are coupled by 57 nuclear reactions. Here, we adopt two established cases in MESA (`make_co_wd` and `wd2`) to perform our simulations. The established case `make_co_wd` is used to build initial models of CO WDs, whereas the established case `wd2` is used to simulate the long-term evolution of He-accreting CO WDs. The established case `wd2` contains an acceleration term in the hydrostatic equilibrium equation so that we can also simulate He-shell flashes.

The initial WD models in our simulations have the following masses (temperatures) in units of $M_\odot$ (10^7K): 0.6 (7.1), 0.7 (7.0), 0.8 (6.9), 0.9 (7.7), 1.0 (10.0), 1.1 (10.4), 1.2 (12.2), 1.25 (13.7), 1.3 (16.0) and 1.35 (20.7). The primordial metallicity for these WDs was taken as 0.02. We performed a large number of calculations of He accretion on to the WDs varying the accretion rates in the range of $\dot{M}_{\rm acc} = 10^{-8}$–$10^{-5}\,M_\odot\,{\rm yr}^{-1}$ with a step size of $\delta \dot{M}_{\rm acc} = 5 \times 10^{-8}\,M_\odot\,{\rm yr}^{-1}$. The accreted He-rich matter consists of 98 per cent He and has a metallicity of 2 per cent. In our calculations, the WDs were resolved with more than 2000 meshpoints.

2.2 Criteria for explosive carbon ignition

The accreted He can be transformed into carbon and oxygen completely if the steady He-shell burning happens on the surface of the accreting WD, increasing the mass of the WD in the process. When the WD mass approaches the Chandrasekhar limit, carbon in its centre will be ignited, which may lead to explosive carbon burning. At that moment, a huge amount of thermonuclear energy is released by the explosive carbon burning and produces a thermonuclear runaway if the energy generated cannot be transported away by convection. The WD will be destroyed by the explosive carbon burning, leading to an SN Ia explosion.

Previous studies supposed that SNe Ia occur when the WDs evolve to the point $t_{\rm b} = 1/22 t_{\rm c}$ (e.g. Lesaffre et al. 2006), where $t_{\rm c}$ is the time-scale it takes a convective element to cross a pressure scaleheight and $t_{\rm b}$ is the exponential temperature growth time caused by the carbon burning. However, the specific point of explosive carbon ignition is still unclear (e.g. Lesaffre et al. 2006; Chen, Han & Meng 2014). In this work, we found that the central density of the WD stops changing but that the temperature increases dramatically after the He-accreting WD reaches the point $t_{\rm b} = 1/22 t_{\rm c}$ in Lesaffre et al. (2006). Similarly to the previous work of Chen, Han & Meng (2014), we take the point when the temperature starts to increase sharply in the centre as the point of the explosive carbon ignition.

3 NUMERICAL RESULTS

3.1 Properties of the He-shell burning

We carried out a series of calculations with initial WD masses of $M^{\rm i}_{\rm WD} = 0.6$–$1.35\,M_\odot$ and accretion rates of $\dot{M}_{\rm acc} = 10^{-8}$–$10^{-5}\,M_\odot\,{\rm yr}^{-1}$. In Fig. 1, we show the stable He-shell burning region in the $M_{\rm WD}$–$\dot{M}_{\rm acc}$ plane, in which the WD can grow steadily in mass. If $\dot{M}_{\rm acc}$ is larger than the maximum accretion rate $\dot{M}_{\rm RG}$ for stable He-shell burning, the envelope of the WD will expand to red-giant size. If $\dot{M}_{\rm acc}$ is below the minimum accretion rate $\dot{M}_{\rm stable}$ for stable He-shell burning, the accreting WD will experience He-shell flashes. The values of $\dot{M}_{\rm stable}$ and $\dot{M}_{\rm RG}$ (in $M_\odot\,{\rm yr}^{-1}$) can be fitted with the following formulae:

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

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

where $M_{\rm WD}$ is in units of $M_\odot$. These two fits were obtained using a bisection method for different WD masses and accretion rates.

It has been supposed that a WD can grow in mass to the Chandrasekhar limit in the stable He-shell burning region and then explode as an SN Ia (e.g. Nomoto 1982a; Wang et al. 2009a). However, in this work, we found that off-centre carbon ignition occurs

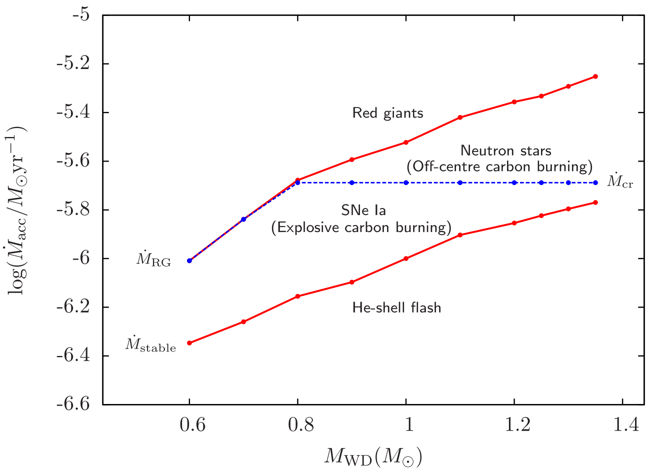

Figure 1. Stable He-shell burning region in the $M_{\rm WD}$–$\dot{M}_{\rm acc}$ plane. The dotted line gives the critical accretion rate above which off-centre carbon ignition occurs when the WD mass approaches the Chandrasekhar limit.

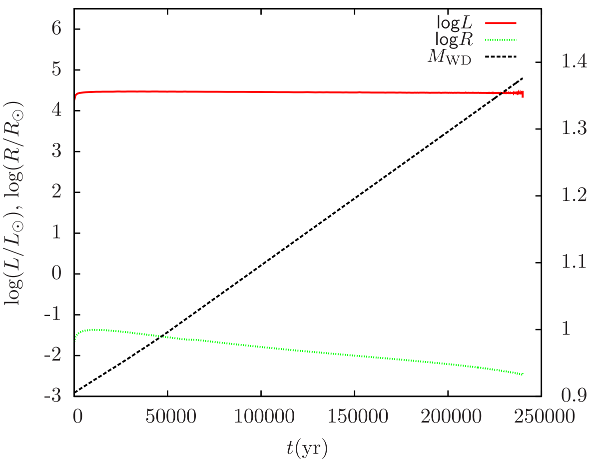

Figure 2. An example of central carbon ignition, in which $M^{\rm i}_{\rm WD} = 0.9\ {\rm M}_\odot$ and $\dot{M}_{\rm acc} = 2 \times 10^{-6}\ {\rm M}_\odot\ {\rm yr}^{-1}$. The long-term evolution of the mass, luminosity and radius of the He-accreting WD is presented.

if $\dot{M}_{\rm acc}$ is above a critical value $\dot{M}_{\rm cr}$ ($\sim 2.05 \times 10^{-6}\ {\rm M}_\odot\ {\rm yr}^{-1}$). Off-centre carbon ignition will convert CO WDs into ONe WDs via an inward-propagating carbon flame, which will ultimately lead to the formation of neutron stars through accretion induced collapse rather than thermonuclear explosions (e.g. Nomoto & Iben 1985; Saio & Nomoto 1985, 1998; Brooks et al. 2016; Schwab, Quataert & Kasen 2016). The WD can increase its mass steadily in the region between $\dot{M}_{\rm stable}$ and $\dot{M}_{\rm cr}$, in which explosive carbon ignition can happen in the centre of the WD, resulting in an SN Ia explosion.

3.2 Centre and off-centre carbon ignition

In Figs 2–5, we present the results of a representative example of central carbon ignition, where $M^{\rm i}_{\rm WD} = 0.9\ {\rm M}_\odot$ and $\dot{M}_{\rm acc} = 2 \times 10^{-6}\ {\rm M}_\odot\ {\rm yr}^{-1}$. Fig. 2 shows the long-term evolution of the mass, luminosity and radius of the He-accreting WD, where the initial central temperature ($T_{\rm c}$) and density ($\rho_{\rm c}$) are 7.7×10^7 K and $1.757 \times 10^7\ {\rm g\,cm^{-3}}$, respectively. This figure shows that the mass of the WD grows linearly with time, as assumed in the model, that the WD radiates at the luminosity corresponding to steady He burning and that the radius of the WD follows the expected mass–radius

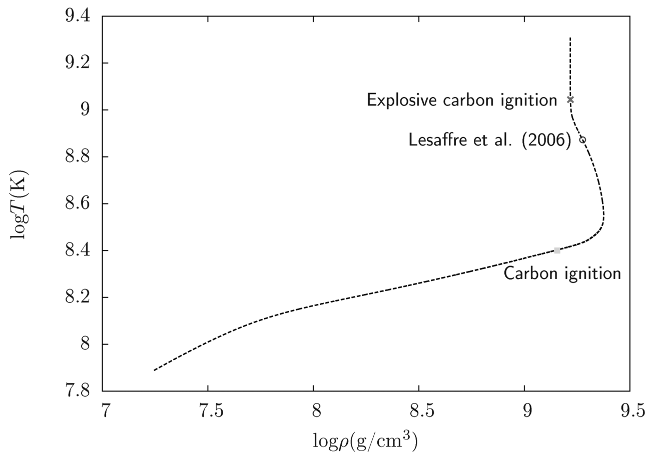

Figure 3. Evolution of $\rho_{\rm c}$ and $T_{\rm c}$ for the He-accreting WD. The red cross shows the starting point for explosive carbon burning that we used, whereas the blue open circle represents the point $t_{\rm b} = 1/22t_{\rm c}$ in Lesaffre et al. (2006). The green filled square indicates the starting point for carbon burning.

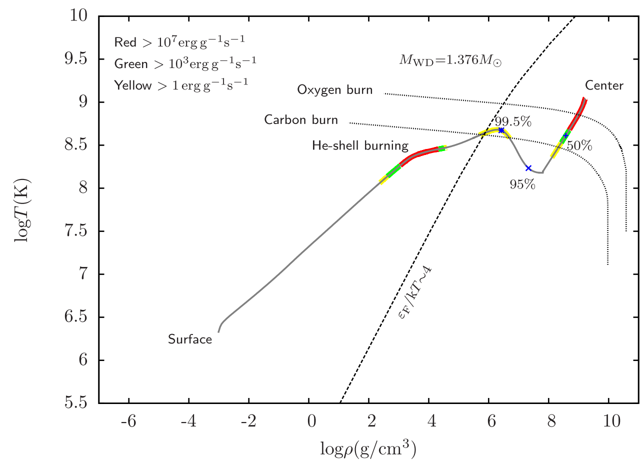

Figure 4. Profile of ρ and T for a $1.376\,{\rm M}_\odot$ WD at the point of explosive carbon ignition. Different mass fractions inside the WD (50 per cent, 95 per cent and 99.5 per cent) are indicated on the profile. Degenerate and non-degenerate regions are separated by the dashed curve ($\varepsilon_{\rm F}/kT \sim 4$), whereas the dotted curves represent the carbon and oxygen burning ignition curves, respectively.

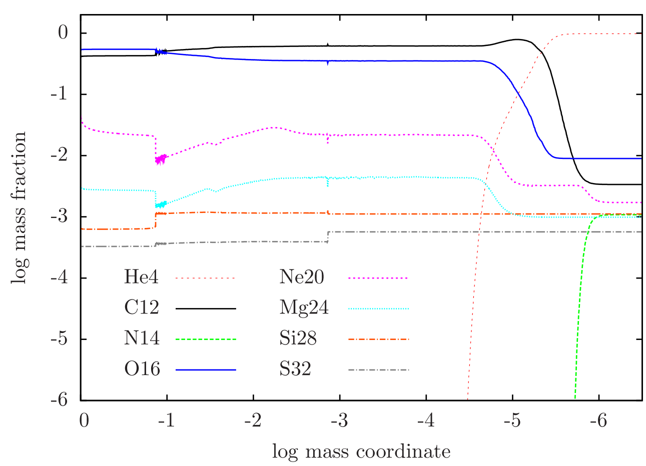

Figure 5. Chemical abundance profile at the point of explosive carbon ignition.

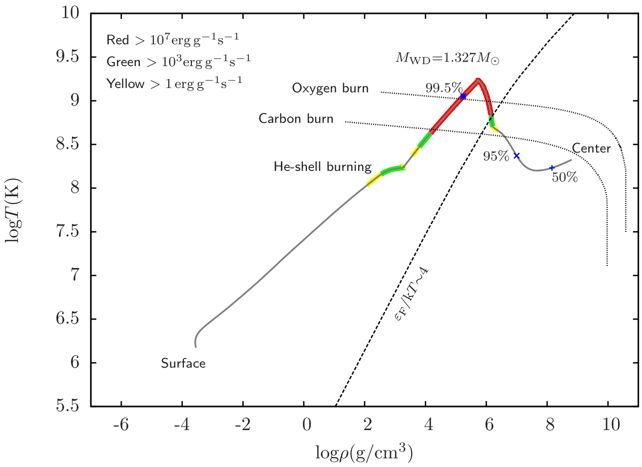

Figure 6. Similar to Fig. 4, but for the ρ–T profile of a 1.327 $M_\odot$ WD at the moment of off-centre carbon ignition, where $M^{\rm i}_{\rm WD} = 1.0\ M_\odot$ and $\dot{M}_{\rm acc} = 3 \times 10^{-6}\ M_\odot\ {\rm yr}^{-1}$

relation. He-shell burning transforms the He-rich matter into carbon and oxygen, increasing the mass of the CO core as a consequence. The He-accreting WD can grow steadily in mass until it approaches a mass of 1.376 $M_\odot$; this phase lasts about 2.35×10^5 yr. It is worth noting that the WD mass at the time of explosion may exceed the Chandrasekhar limit if rotation is taken into account (e.g. Yoon & Langer 2004; Chen & Li 2009; Justham 2011; Hachisu et al. 2012; Wang et al. 2014b).

In Fig. 3, we show the whole evolution of $\rho_{\rm c}$ and $T_{\rm c}$ of the He-accreting WD. After about 2.27×10^5 yr, carbon is ignited in the centre of the He-accreting WD, but initially is non-explosive as the thermonuclear energy is transported away by convection. At the end of the simulation, $\rho_{\rm c}$ no longer evolves, but the nuclear reaction rate of carbon burning in the centre of the WD increases quickly with $T_{\rm c}$, which we identify with the start of *explosive* carbon burning. The WD in our simulations can grow in mass to the condition of explosive carbon ignition, resulting in an SN Ia explosion. It takes about 8×10^3 yr from the point of carbon ignition to explosive carbon burning.

Fig. 4 shows the ρ–T profile of the WD when explosive carbon ignition occurs, where ρ and T reach maximum values of $1.65 \times 10^9\ {\rm g\,cm^{-3}}$ and 1.11×10^9 K, respectively. At this moment, a deflagration wave starts to spread from the centre of the WD. In Fig. 5, we present the profile of some key chemical abundances at the moment of explosive carbon ignition for this particular example. The accreted He is burnt into carbon, oxygen and other intermediate-mass elements in the outer layer of the WD core. This chemical abundance profile can be taken as initial input for SN Ia explosion models. The abundance profile (together with density, temperature, etc.) varies for different initial models and is made available on request by contacting BW.

If $\dot{M}_{\rm acc}$ is larger than $\dot{M}_{\rm cr}$, the He-accreting WD will experience off-centre carbon ignition, similar to what happens during the merging of double CO WDs (for more discussion see Section 5). In Fig. 6, we present a representative example of off-centre carbon ignition, where $M^{\rm i}_{\rm WD} = 1.0\ M_\odot$ and $\dot{M}_{\rm acc} = 3 \times 10^{-6}\ M_\odot\ {\rm yr}^{-1}$. In this case, it is the compressional heating of the outer layers caused by fast accretion that leads to off-centre ignition. Off-centre carbon ignition occurs in this example when the WD reaches a mass of 1.327 $M_\odot$, while He-shell burning continues on the surface of the WD. It takes 1.08×10^5 yr from the beginning of mass

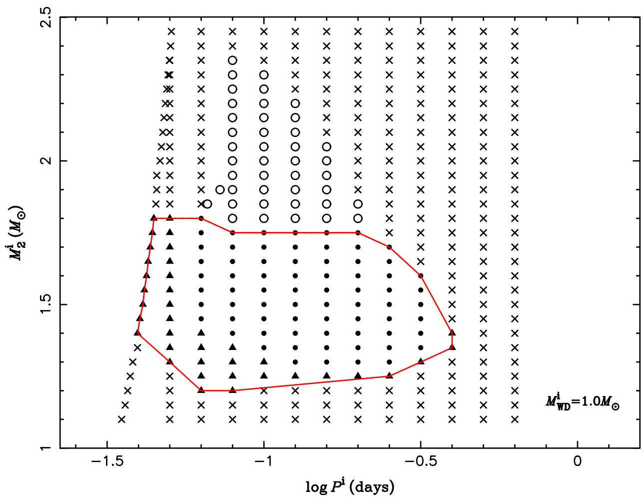

Figure 7. Initial parameter space for SNe Ia in the log $P^{\rm i}$–$M^{\rm i}_2$ plane for $M^{\rm i}_{\rm WD} = 1.0\ M_\odot$. The filled symbols represent systems that lead to SN Ia explosions, where the filled triangles and circles indicate that the WDs explode as SNe Ia in the weak He-shell flash stage or in the stable He-shell burning stage, respectively. Open circles show systems that experience off-centre carbon ignition, resulting in the eventual formation of neutron stars. Crosses denote systems that experience strong He-shell flashes that prevent WDs from growing in mass to the Chandrasekhar limit.

accretion to the condition of off-centre carbon ignition. The resulting carbon burning front likely propagates inwards in a quiet manner, forming first an ONe WD but ultimately collapsing to form a neutron star rather than an SN Ia (e.g. Nomoto & Iben 1985; Saio & Nomoto 1985, 1998; Brooks et al. 2016).

4 THE HE STAR DONOR CHANNEL

4.1 Initial parameter space for SNe Ia

Wang et al. (2009a) carried out a systematic study of the He star donor channel for the progenitors of SNe Ia. They performed binary evolution calculations of the donor star with the Cambridge stellar evolution code (Eggleton 1973; Han, Podsiadlowski & Eggleton 1994; Pols et al. 1998) to determine the initial parameter space of WD binaries that can result in SNe Ia in the orbital period–secondary mass (log $P^{\rm i}$–$M^{\rm i}_2$) plane. Using these results and adopting a detailed BPS approach, Wang et al. (2009b) then obtained the SN Ia rates and delay times for the He star donor channel. However, Wang et al. (2009a) did not take into account the possibility of off-centre carbon ignition, which will reduce the initial parameter space for SNe Ia and decrease the theoretical SN Ia rates. In this work, we extract the mass-transfer rate from the data files of the binary evolution calculations in Wang et al. (2009a) and assume that off-centre carbon burning happens if the mass-transfer rate is higher than the critical value $\dot{M}_{\rm cr}$ in Section 3.1 when the CO WD grows in mass close to the Chandrasekhar limit.

Fig. 7 shows the final outcomes of the binary evolution calculations in the log $P^{\rm i}$–$M^{\rm i}_2$ plane for $M^{\rm i}_{\rm WD} = 1.0\ M_\odot$, where the filled symbols indicate systems that result in SN Ia explosions. The filled triangles and circles in this figure denote that the WDs explode as SNe Ia in the weak He-shell flash stage and in the stable He-shell burning stage, respectively. Some systems fail to form SNe Ia because strong He-shell flashes prevent the WDs from growing in mass to the Chandrasekhar limit (the crosses in Fig. 7). The open circles indicate systems that experience off-centre carbon ignition

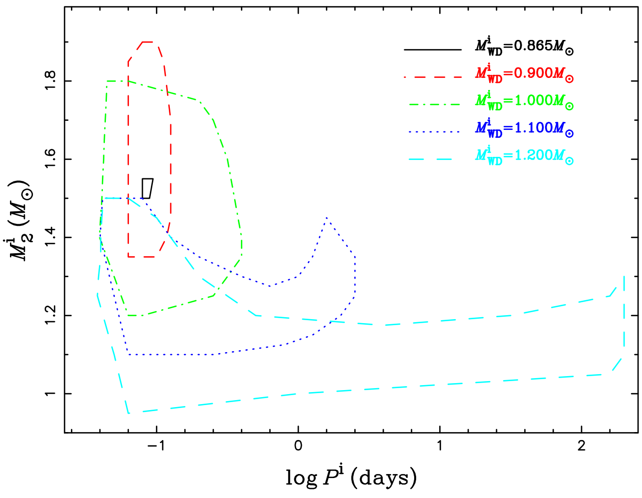

Figure 8. Initial parameter space for SNe Ia in the log $P^{\rm i}$–$M_2^{\rm i}$ plane for different values of $M_{\rm WD}^{\rm i}$.

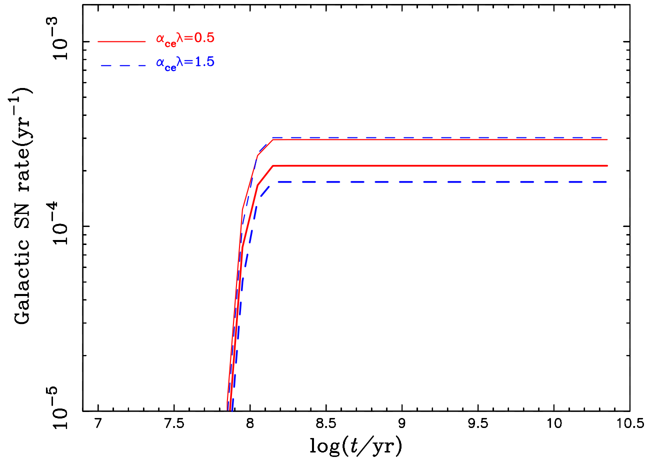

Figure 9. Rates of SNe Ia in the Galaxy for a constant star formation rate of 5 $M_{\odot}$ yr^{-1}. The thick curves are the results based on the initial contours in Fig. 8, whereas the thin curves are the results from Wang et al. (2009a). Different line styles are for different values of $\alpha_{\rm ce}\lambda$ as indicated in the figure.

and ultimately produce neutron stars; these had been assumed to produce SNe Ia in Wang et al. (2009a).

In Fig. 8, we present the initial parameter space for SNe Ia in the log $P^{\rm i}$–$M_2^{\rm i}$ plane for different values of $M_{\rm WD}^{\rm i}$. For $M_{\rm WD}^{\rm i}$ = 0.865 $M_{\odot}$, which is close to the minimum WD mass for producing SNe Ia in the He star donor channel, the possible parameter space is quite small. The upper boundaries of the parameter space are mainly constrained by the condition for off-centre carbon ignition due to a high mass-transfer rate when the WDs grow in mass close to the Chandrasekhar limit, which is strongly dependent on the initial mass of the WD. The lower boundaries are set by the condition that the mass-transfer rate should be high enough to ensure that the WD can increase its mass to the Chandrasekhar limit. The left-hand boundaries are determined by the minimum value of log $P^{\rm i}$, for which a zero-age He MS star would fill its Roche lobe. WD+He star systems beyond the right-hand boundaries experience a very high mass-transfer rate because of the rapid expansion of He stars during the subgiant phase; this drastically reduces the donor-star mass through an optically thick wind (e.g. Hachisu, Kato & Nomoto 1996); some of these systems may contribute to the formation of double CO WDs and produce SNe Ia through the DD model (e.g. Ruiter et al. 2013; Liu et al. 2016).

The results obtained here are very similar to those of Brooks et al. (2016), as can be seen, for example, by comparing these to fig. 3 from their paper. The main difference is that Brooks et al. (2016) have computed full binary evolution calculations of CO WD+He star systems and thus computed the (time-varying) mass accretion rates on to the WD self-consistently instead of assuming constant accretion rates. The resulting limits on the He donor mass leading to SNe Ia (about 1.3–1.7 $M_{\odot}$) are nevertheless very similar in the two methods, at least for an initial WD mass of 1.0 $M_{\odot}$.

4.2 BPS results

To obtain SN Ia rates for the He star donor channel, we carried out a series of Monte Carlo BPS calculations based on the Hurley binary evolution code (see Hurley, Tout & Pols 2002). The basic BPS setup and principal assumptions here are similar to those of Wang et al. (2009b), but in this work, we used the updated initial parameter space for SNe Ia presented in Fig. 8. In each BPS simulation, the evolution of 4×10^7 sample binaries is tracked from the primordial binary stage to the production of the WD+He star systems (see Wang et al. 2009b). We suppose that, if the initial parameters of a WD+He star system are located inside the SN Ia parameter space of Fig. 8, an SN Ia explosion happens. To obtain the outcome of the common-envelope ejection, the commonly used energy equation of Webbink (1984) is employed. As in previous calculations, a free parameter $\alpha_{\rm ce}\lambda$ is used to calculate the process of the common-envelope evolution, and its value is set to 0.5 or 1.5 (e.g. Wang et al. 2009b).

In Fig. 9, we present the rates of SNe Ia in the Galaxy by adopting a metallicity $Z = 0.02$ and star formation rate of 5 $M_{\odot}$yr^{-1}. This work leads to an SN Ia rate of $\sim 0.2 \times 10^{-3}$ yr^{-1} (thick curves in Fig. 9) based on the initial parameter space in Fig. 8, which is lower than the observed estimate of $\sim 3 \times 10^{-3}$ yr^{-1} (e.g. Cappellaro & Turatto 1997). This indicates that the He star donor channel contributes to only a small fraction of all SNe Ia (∼7 per cent); some other mechanisms or formation channels are therefore required to produce all SNe Ia (see, e.g. Tout 2005; Wang & Han 2012). If we adopt the larger initial contours for producing SNe Ia in Wang et al. (2009a), the SN Ia rates will increase to $\sim 0.3 \times 10^{-3}$ yr^{-1} (thin curves in Fig. 9), which are higher than the results in this work but not significantly so. The reason is that WD binaries with larger He donor masses, which also form SNe Ia in Wang et al. (2009a), do not contribute significantly in the BPS simulations. Accounting for off-centre carbon ignition changes the overall SN Ia rate of this channel but has no effect on the shape of the delay-time distribution. Note that SNe Ia from this channel happen systemically earlier in high-metallicity environments (see Wang & Han 2010b).

5 DISCUSSION

In the classical DD model, SNe Ia arise from the merging of two CO WDs that are brought together by gravitational wave radiation and have a total mass above the Chandrasekhar limit (e.g. Iben & Tutukov 1984; Webbink 1984; Yungelson & Kuranov 2017). However, a fundamental challenge to this model is that off-centre carbon ignition due to a high mass-accretion rate during the merger (or in the post-merger cooling phase; Yoon, Podsiadlowski & Rosswog 2007) is likely to convert the CO WDs into ONe WDs through an inward-propagating carbon flame; ONe WDs would collapse into neutron stars as core accretion continues (e.g. Nomoto & Iben 1985; Saio

& Nomoto 1985, 1998; Kawai, Saio & Nomoto 1987; Timmes, Woosley & Taam 1994; Yoon et al. 2007; Shen et al. 2012; Schwab, Quataert & Bildsten 2015). For the merging of two CO WDs, it has been suggested that the critical mass-accretion rate for off-centre carbon burning is close to $2 \times 10^{-6}\,\mathrm{M_{\odot}\,yr^{-1}}$ (e.g. Saio & Nomoto 1985; Kawai, Saio & Nomoto 1987). In this work, we also found that off-centre carbon ignition will happen if the accretion rate is above a critical value ($\sim 2.05 \times 10^{-6}\,\mathrm{M_{\odot}\,yr^{-1}}$). By considering off-centre carbon burning, we found that the Galactic SN Ia rate from the He star donor channel decreases from $\sim 0.3 \times 10^{-3}$ to $\sim 0.2 \times 10^{-3}\,\mathrm{yr^{-1}}$. On the other hand, off-centre carbon burning contributes to the formation of neutron stars, which will increase the rate of accretion induced collapse that needs to be studied in the future.

In this work, we used hot WDs to simulate He accretion on to WDs. Chen et al. (2014) recently explored the effect of different cooling times and found that it affects the conditions at carbon ignition (see also Lesaffre et al. 2006; Brooks et al. 2016). It may thus also affect the critical accretion rate separating centre and off-centre carbon ignition; a cold WD needs a thick He layer for off-centre carbon ignition. Another limitation is the (necessary) assumption of spherical symmetry in the stellar evolution code. Any possible 3D effects on the ignition of carbon, especially for off-centre conditions, are therefore ignored. In reality, ignition will start at one location in the shell and not simultaneously over the entire shell. Most relevant for this study is the fact that the accreting WD will be rotating quite rapidly, which may change the conditions for off-centre carbon ignition and may also affect how carbon burning proceeds afterwards. These uncertainties should be explored in the future.

It has been suggested that HD 49798 (a hydrogen stripped subdwarf O6 star) with its X-ray pulsating companion (a massive WD) is a strong progenitor candidate for an SN Ia (e.g. Wang & Han 2010a; Mereghetti et al. 2011; Liu et al. 2015). Due to the rapid expansion of HD 49798's envelope, it will fill its Roche lobe in about 4×10^{4} yr (see Wang & Han 2010a). In this binary, off-centre carbon burning may happen when the WD grows in mass close to the Chandrasekhar limit due to the high mass-transfer rate ($>2.05 \times 10^{-6}\,\mathrm{M_{\odot}\,yr^{-1}}$; see fig. 2 of Wang & Han 2010a). Thus, we speculate that the massive WD in this binary may eventually form a neutron star and not produce an SN Ia. In addition, SN 2012Z may originate from the evolution of a hybrid CONe WD+He star system (see Wang et al. 2014a).

For the He star donor channel, the mass donor would survive and should be observable after the SN explosion (see Wang & Han 2009). The identification of the surviving donors would support this progenitor channel (e.g. Podsiadlowski 2010; Liu et al. 2012). Wang & Han (2009) studied the properties of the surviving donors of SNe Ia based on the He star donor channel and suggested that this channel is an alternative way for the formation of hypervelocity He stars such as US 708 (see also Justham et al. 2009; Geier et al. 2015). In order to study the surviving donors of the He star donor channel, some hydrodynamical simulations related to the impact of the SN explosion on the He donors were performed (e.g. Pan, Ricker & Taam 2010, 2013; Liu et al. 2013). It can be expected that more hypervelocity He stars originating as surviving donors of SNe Ia are discovered by some of the ongoing surveys, for example, the Hyper-MUCHFUSS project (e.g. Geier et al. 2011, 2015; Tillich et al. 2011) and the LAMOST LEGUE survey (e.g. Deng et al. 2012).

In this work, we calculated the long-term evolution of He-accreting WDs with $\dot{M}_{\rm acc} > 4 \times 10^{-8}\,\mathrm{M_{\odot}\,yr^{-1}}$. However, if $\dot{M}_{\rm acc}$ is too low (e.g. $<4 \times 10^{-8}\,\mathrm{M_{\odot}\,yr^{-1}}$), the CO core cannot grow in mass but a thick He-shell will develop on the surface of the WD (e.g. Woosley, Taam & Weaver 1986). Under these conditions, a double-detonation may occur in a sub-Chandrasekhar WD if the mass of the He-shell reaches a critical value (e.g. Nomoto 1982b; Iben & Tutukov 1989; Livne 1990; Höflich & Khokhlov 1996; Neunteufel, Yoon & Langer 2016). Wang, Justham & Han (2013) obtained the parameter space in the double-detonation model for producing SNe Ia and suggested that this model could explain the formation of type Iax SNe (a sub-type of sub-luminous SNe Ia similar to SN 2002cx; e.g. Foley et al. 2013). It has been thought that CD −30° 11223 (a WD+He star system) may form an SN Ia via the double-detonation model in its future evolution (see Geier et al. 2013; Wang, Justham & Han 2013). Note, however, that current simulations of the double-detonation model still fail to reproduce many of the main properties of observed SNe Ia (e.g. Kromer et al. 2010).

This work involved only single-shell (He-shell) burning on the surface of a WD, in which the WD can grow in mass to the Chandrasekhar limit through steady He-shell burning and finally produce an SN Ia. In the standard SD model, a WD can also obtain H-rich matter from its non-degenerate donor that leads to double-shell (H-/He-shell) burning; The accumulated H-rich matter in this case is first burnt into He and then converted into carbon and oxygen. However, it is still difficult for the WD to grow in mass to the Chandrasekhar limit as stable H and He burning require different mass growth rates (e.g. Idan, Shaviv & Shaviv 2013; Hillman et al. 2016). This fundamental difficulty for double-shell burning on the surface of the WD needs to be resolved in future studies.

6 SUMMARY

By employing the MESA stellar evolution code, we carried out a series of simulations of He accretion on to CO WDs. In each simulation, we calculated the evolution of the He-accreting WD for a sufficiently long time to determine their detailed properties at the time of carbon ignition. We found that He-accreting WDs in the stable He burning region will experience either centre or off-centre carbon ignition when the WDs approach the Chandrasekhar limit. When off-centre carbon burning is included, the Galactic rate of SNe Ia for the He star donor channel decreases from $\sim 0.3 \times 10^{-3}$ to $\sim 0.2 \times 10^{-3}\,\mathrm{yr^{-1}}$. Importantly, this work indicates that a WD can grow in mass to the Chandrasekhar limit through steady He accretion and eventually produce an SN Ia. We also produce the chemical abundance profile of the WD at the time of the SN explosion, which can be used as initial input for SN Ia explosion models. To set constraints on the He star donor channel, large samples of observed massive WD+He star systems and the surviving donors are needed. Finally, the process of H/He accretion on to WDs still needs further study.

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REFERENCES

Bours M. C. P., Toonen S., Nelemans G., 2013, A&A, 552, A24
Brooks J., Bildsten L., Marchant P., Paxton B., 2015, ApJ, 807, 74
Brooks J., Bildsten L., Schwab J., Paxton B., 2016, ApJ, 821, 28

Cappellaro E., Turatto M., 1997, in Ruiz-Lapuente P., Cannal R., Isern J., eds, Thermonuclear Supernovae. Kluwer, Dordrecht, p. 77
Chen W.-C., Li X.-D., 2009, ApJ, 702, 686
Chen X.-F., Han Z., Meng X.-C., 2014, MNRAS, 438, 3358
Claeys J. S. W., Pols O. R., Izzard R. G., Vink J., Verbunt F. W. M., 2014, A&A, 563, A83
Cooper M. C., Newman J. A., Yan R., 2009, ApJ, 704, 687
Deng L. et al., 2012, Res. Astron. Astrophys., 12, 735
Diehl R. et al., 2014, Science, 345, 1162
Eggleton P. P., 1973, MNRAS, 163, 279
Foley R. J. et al., 2013, ApJ, 767, 57
Geier S., Nesslinger S., Heber U., Przybilla N., Napiwotzki R., Kudritzki R.-P., 2007, A&A, 464, 299
Geier S. et al., 2011, A&A, 530, A28
Geier S. et al., 2013, A&A, 554, A54
Geier S. et al., 2015, Science, 347, 1126
Hachisu I., Kato M., Nomoto K., 1996, ApJ, 470, L97
Hachisu I., Kato M., Saio H., Nomoto K., 2012, ApJ, 744, 69
Han Z., Podsiadlowski Ph., 2004, MNRAS, 350, 1301
Han Z., Podsiadlowski Ph., 2006, MNRAS, 368, 1095
Han Z., Podsiadlowski P., Eggleton P. P., 1994, MNRAS, 270, 121
Hillebrandt W., Kromer M., Röpke F. K., Ruiter A. J., 2013, Frontiers Phys., 8, 116
Hillman Y., Prialnik D., Kovetz A., Shara M. M., 2016, ApJ, 819, 168
Höflich P., Khokhlov A., 1996, ApJ, 457, 500
Höflich P., Dragulin P., Mitchell J., Penney B., Sadler B., Diamond T., Gerardy C., 2013, Frontiers Phys., 8, 144
Howell D. A., 2011, Nat. Commun., 2, 350
Hoyle F., Fowler W. A., 1960, ApJ, 132, 565
Hurley J. R., Tout C. A., Pols O. R., 2002, MNRAS, 329, 897
Iben I., Tutukov A. V., 1984, ApJS, 54, 335
Iben I., Tutukov A. V., 1989, ApJ, 342, 430
Idan I., Shaviv N. J., Shaviv G., 2013, MNRAS, 433, 2884
Justham S., 2011, ApJ, 730, L34
Justham S., Wolf C., Podsiadlowski P., Han Z., 2009, A&A, 493, 1081
Kato M., Hachisu I., 2004, ApJ, 613, L129
Kato M., Hachisu I., Kiyota S., Saio H., 2008, ApJ, 684, 1366
Kawai Y., Saio H., Nomoto K., 1987, ApJ, 315, 229
Kromer M., Sim S. A., Fink M., Röpke F. K., Seitenzahl I. R., Hillebrandt W., 2010, ApJ, 719, 1067
Langer N., Deutschmann A., Wellstein S., Höflich P., 2000, A&A, 362, 1046
Lesaffre P., Han Z., Tout C. A., Podsiadlowski Ph., Martin R. G., 2006, MNRAS, 368, 187
Li X.-D., van den Heuvel E. P. J., 1997, A&A, 322, L9
Liu W., Chen W., Wang B., Han Z., 2010, A&A, 523, A3
Liu Z., Pakmor R., Röpke F. K., Edelmann P., Wang B., Kromer M., Hillebrandt W., Han Z., 2012, A&A, 548, A2
Liu Z. et al., 2013, ApJ, 774, 37
Liu D., Zhou W., Wu C., Wang B., 2015, Res. Astron. Astrophys., 15, 1813
Liu D., Wang B., Podsiadlowski Ph., Han Z., 2016, MNRAS, 461, 3653
Lü G., Zhu C., Wang Z., Wang N., 2009, MNRAS, 396, 1086
Mannucci F., Della Valle M., Panagia N., 2006, MNRAS, 370, 773
Maoz D., Mannucci F., Nelemans G., 2014, ARA&A, 52, 107
Matteucci F., Greggio L., 1986, A&A, 154, 279
Maxted P. F. L., Marsh T. R., North R. C., 2000, MNRAS, 317, L41
McCully C. et al., 2014, Nature, 512, 54
Meng X., Podsiadlowski Ph., 2017, MNRAS, 469, 4763
Meng X., Yang W., 2012, A&A, 543, A137
Meng X., Gao Y., Han Z., 2015, Int. J. Mod. Phys., 24, 1530029
Mereghetti S., La Palombara N., Tiengo A., Pizzolato F., Esposito P., Woudt P. A., Israel G. L., Stella L., 2011, ApJ, 737, 51
Nelemans G., Yungelson L. R., Portegies Zwart S. F., Verbunt F., 2001, A&A, 365, 491
Neunteufel P., Yoon S.-C., Langer N., 2016, A&A, 589, A43
Nomoto K., 1982a, ApJ, 253, 798
Nomoto K., 1982b, ApJ, 257, 780
Nomoto K., Iben I., 1985, ApJ, 297, 531
Nomoto K., Iwamoto K., Kishimoto N., 1997, Science, 276, 1378
Pan K.-C., Ricker P. M., Taam R. E., 2010, ApJ, 715, 78
Pan K.-C., Ricker P. M., Taam R. E., 2013, ApJ, 773, 49
Paxton B., Bildsten L., Dotter A., Herwig F., Lessafre P., Timmes F., 2011, ApJS, 192, 3
Paxton B. et al., 2013, ApJS, 208, 4
Paxton B. et al., 2015, ApJS, 220, 15
Piersanti L., Tornambé A., Yungelson L. R., 2014, MNRAS, 445, 3239
Piersanti L., Tornambé A., Yungelson L. R., 2015, MNRAS, 452, 2897
Podsiadlowski Ph., 2010, Astron. Nachr., 331, 218
Podsiadlowski Ph., Mazzali P., Lesaffre P., Han Z., Förster F., 2008, New Astron. Rev., 52, 381
Pols O. R., Schröder K. P., Hurly J. R., Tout C. A., Eggleton P. P., 1998, MNRAS, 298, 525
Ruiter A. J. et al., 2013, MNRAS, 429, 1425
Ruiter A. J., Belczynski K., Sim S. A., Seitenzahl I. R., Kwiatkowski D., 2014, MNRAS, 440, L101
Ruiz-Lapuente P., 2014, New Astron. Rev., 62, 15
Saio H., Nomoto K., 1985, A&A, 150, L21
Saio H., Nomoto K., 1998, ApJ, 500, 388
Schwab J., Quataert E., Bildsten L., 2015, MNRAS, 453, 1910
Schwab J., Quataert E., Kasen D., 2016, MNRAS, 463, 3461
Shen K. J., Bildsten L., Kasen D., Quataert E., 2012, ApJ, 748, 35
Thomson M. G., Chary R. R., 2011, ApJ, 731, 72
Tillich A. et al., 2011, A&A, 527, A137
Timmes F. X., Woosley S. E., Taam R. E., 1994, ApJ, 420, 348
Toonen S., Nelemans G., Portegies Zwart S., 2012, A&A, 546, A70
Toonen S., Claeys J. S. W., Mennekens N., Ruiter A. J., 2014, A&A, 562, A14
Tout C. A., 2005, in Hameury J.-M., Lasota J.-P., eds, ASP Conf. Ser, Vol. 330, The astrophysics of cataclysmic variables and related objects. Astron. Soc. Pac., San Francisco, p. 279
Vennes S., Kawka A., O'Toole S. J., Németh P., Burton D., 2012, ApJ, 759, L25
Wang B., Han Z., 2009, A&A, 508, L27
Wang B., Han Z., 2010a, Res. Astron. Astrophys., 10, 681
Wang B., Han Z., 2010b, A&A, 515, A88
Wang B., Han Z., 2012, New Astron. Rev., 56, 122
Wang B., Meng X., Chen X., Han Z., 2009a, MNRAS, 395, 847
Wang B., Chen X., Meng X., Han Z., 2009b, ApJ, 701, 1540
Wang B., Li X., Han Z., 2010, MNRAS, 401, 2729
Wang B., Justham S., Han Z., 2013, A&A, 559, A94
Wang B., Meng X., Liu D., Liu Z., Han Z., 2014a, ApJL, 794, L28
Wang B., Justham S., Liu Z., Zhang J., Liu D., Han Z., 2014b, MNRAS, 445, 2340
Wang B., Li Y., Ma X., Liu D., Cui X., Han Z., 2015, A&A, 584, A37
Webbink R. F., 1984, ApJ, 277, 355
Whelan J., Iben I., 1973, ApJ, 186, 1007
Woosley S. E., Taam R. E., Weaver T. A., 1986, ApJ, 301, 601
Woudt P. A. et al., 2009, ApJ, 706, 738
Wu C., Liu D., Zhou W., Wang B., 2016, Res. Astron. Astrophys., 16, 160
Wu C., Wang B., Liu D., Han Z., 2017, A&A, 604, A31
Yoon S.-C., Langer N., 2003, A&A, 412, L53
Yoon S.-C., Langer N., 2004, A&A, 419, 623
Yoon S.-C., Podsiadlowski Ph., Rosswog S., 2007, MNRAS, 380, 933
Yungelson L. R., Kuranov A. G., 2017, MNRAS, 464, 1607
Ziegerer E., Heber U., Geier S., Irrgang A., Kupfer T., Fürst F., Schaffenroth J., 2017, A&A, 601, A58

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