The C/O ratio of He-accreting carbon-oxygen white dwarfs and type Ia supernovae

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Abstract Type Ia supernovae (SNe Ia) are thermonuclear explosions of carbon-oxygen white dwarfs (CO WDs), and are believed to be excellent cosmological distance indicators due to their high luminosity and remarkable uniformity. However, there exists a diversity among SNe Ia, and a poor understanding of the diversity hampers the improvement of the accuracy of cosmological distance measurements. The variations of ratios of carbon to oxygen (C/O) of WDs at explosion are suggested to contribute to the diversity. In the canonical model of SNe Ia, a CO WD accretes matter from its companion and increases its mass till Chandrasekhar mass limit when the WD explodes. In this work, we studied the C/O ratio for accreting CO WDs. Employing the stellar evolution code MESA, we simulated the accretion of He-rich material onto CO WDs with different initial WD masses and different mass accretion rates. We found that the C/O ratio varies for different cases. The C/O ratio of the He-accreting CO WDs at explosion increases with a decreasing initial WD mass or a decreasing accretion rate. The various C/O ratios may, therefore, contribute to the diversity of SNe Ia.

Key words: stars: evolution — supernovae: general — white dwarfs

1 INTRODUCTION

Type Ia supernovae (SNe Ia) are of great importance in astrophysics. They have been successfully used as standardizable candles for measuring cosmological distances due to their high luminosity and remarkable uniformity, leading to the discovery of the accelerating expansion of the universe which is driven by dark energy (Riess et al. 1998; Perlmutter et al. 1999). Besides, SNe Ia are also important for the evolution of their host galaxies since many heavy elements can be produced during their explosions (Greggio & Renzini 1983; Matteucci & Greggio 1986; Rana 1991). Besides, they are accelerators of cosmic rays (e.g., Helder et al. 2009; Fang & Zhang 2012).

Hoyle & Fowler (1960) suggested that SNe Ia result from thermonuclear explosions of carbon-oxygen white dwarfs (CO WDs) in close binaries. Once a CO WD increases its mass close to the Chandrasekhar mass limit, the carbon in the degenerate core is ignited, and the explosive carbon burning may destroy the WD and explodes as a SN Ia (Nomoto et al. 1984). However, no progenitor system before SN Ia explosion has been conclusively identified (Wang 2018). Currently, many different kinds
of progenitor models of SNe Ia have been proposed (see Wang & Han 2012 for a review), and the most favourable models are the single-degenerate (SD) model and the double-degenerate (DD) model. For the SD model, a CO WD accretes material from its non-degenerate companion, the WD grows in mass till it is close to the Chandrasekar mass limit and explodes as a SN Ia (Whelan & Iben 1973; Nomoto et al. 1984; Hachisu et al. 1996; Li & van den Heuvel 1997; Han & Podsiadlowski 2004; Wang et al. 2009; Meng et al. 2009; Hillman et al. 2016; Meng & Podsiadlowski 2017). For the DD model, a SN Ia arises from the coalescence of two CO WDs due to angular momentum loss via gravitational wave radiation and the explosion might happen if the combined mass of the merger is larger than the Chandrasekar mass limit (Sparks & Stecher 1974; Iben & Tutukov 1984; Webbink 1984; Han 1998; Chen et al. 2012).

When SNe Ia are applied as distance indicators, the Phillips relation (Phillips 1993) is adopted. However, there exists spectroscopic diversity among SNe Ia that is presently not well understood, nor how this diversity is linked to the properties of their progenitors (Branch et al. 1995; Wang & Han 2012). Arnett (1982) suggested that the amount of $^{56}\text{Ni}$ formed during a SN Ia explosion dominates its maximum luminosity. Nevertheless, the origin of the variation in the amount of $^{56}\text{Ni}$ for different SNe Ia is still unclear (Podsiadlowski et al. 2008). It has been suggested that the ratio of carbon to oxygen (C/O) of a WD at the moment of the SN explosion is the dominant parameter for the Phillips relation. That is to say, the higher the C/O ratio, the larger the amount of $^{56}\text{Ni}$ (Umeda et al. 1999b), and then the higher the maximum luminosity. Meng et al. (2009) and Meng & Yang (2010) studied the initial masses of CO WDs in SNe Ia progenitors with a binary population synthesis approach. They showed that the masses vary with population age and explains the brightness difference of SNe Ia between spiral galaxies and elliptical galaxies qualitatively if C/O ratios (related to the initial masses of CO WDs) dominate the amount of $^{56}\text{Ni}$ produced. Recently we have made detailed stellar evolution calculations for the accreting CO WDs, and found that the C/O ratios for accreting WDs are higher than that previously believed (Cui et al. 2018). However, the C/O ratios for accreting WDs at explosion are still not known. The ratios may influence the brightness of SNe Ia and the diversity of SNe Ia.

The purpose of this paper is to study the C/O ratios of He-accreting CO WDs at explosion in the SD model. Previous works have shown that the region of accretion rates for the steady hydrogen shell burning is significantly lower than that for steady helium shell burning (Ma et al. 2013; Wang et al. 2015), and hydrogen-rich material accretion leads to helium shell flashes (Cui et al. 2018) as a result. Therefore it is unrealistic to do calculations that follow the accretion of H-rich material till the explosion. In this paper, we use the stellar evolution code MESA to simulate the accreting process, letting WDs accrete He-rich material. We describe our primary method and simulation code in Section 2, and present the results in Section 3. Finally, we discuss and conclude in Sections 4 and 5.

2 METHODS

We employ the stellar evolution code MESA (version5329) (Paxton et al. 2011, 2013, 2015, 2018) to simulate the accretion of He-rich material onto CO WDs. Two relevant MESA suite cases (make_co_wd and wd2) were used for our simulations. The suite case make_co_wd is used to create initial CO WD models. We can create different kinds of WDs ($Z = 0.02$) by using the suite case make_co_wd, and simulate the accretion of the He-rich material ($Y = 0.98, Z = 0.02$) onto WDs by using the suite case wd2. The nuclear network consisted of isotopes needed for helium, carbon and oxygen burning, which are coupled by more than 50 nuclear reactions.

Wang et al. (2015) and Wang et al. (2017) have obtained the steady burning region for helium accretion onto CO WDs. We follow the work of Wang et al. (2015) and Wang et al. (2017), adopting their $M_{\text{Edd}}$ and $M_{\text{stable}}$. Moreover, Wang et al. (2017) found a critical accretion rate above which off-centre carbon ignition occurs when the WD mass approaches the Chandrasekhar mass limit. Since we want to study the C/O ratio for the WD at explosion of SN Ia, the parameter space for WDs and accretion rates we use in our study can only be selected in the region where explosive carbon burning is shown by Wang et al. (2017) to occur. The initial WD masses are, therefore, chosen to be 0.8, 0.9, 1.0, 1.1$M_\odot$ and the accretion rates are $1.4, 1.6, 1.8, 2.0 \times 10^{-6} M_\odot\text{yr}^{-1}$ in our simulations. We only...
select the initial parameters that helium shell burning could be steady during the evolution so that the mass retention efficiency of helium shell burning is about 100%. However, it is difficult to determine the lower boundary of the steady burning region (Kato & Hachisu 2004; Piersanti et al. 2014; Wang et al. 2015, 2017). The WD may undergo several flashes before steady burning if the $\dot{M}_{\text{acc}}$ is close to the lower boundary. Nevertheless, these flashes could hardly affect the results.

An accreting WD grows in mass via steady helium shell burning and finally approaches the Chandrasekhar mass limit. Carbon may be ignited in the centre, and the carbon burning can be explosive. To determine the start point of explosive carbon ignition in the simulation, Lesaffre et al. (2006) suggested that SNe Ia explosion occurs when the accreting WDs evolve to the point $t_b = 1/22 t_c$, where $t_b$ is the exponential temperature growth time of carbon burning and $t_c$ is a convective element crossing time over a pressure scale height. Chen et al. (2014) and Wu et al. (2016), however, chose the point where the central temperature of the WD increases sharply, but the central density of the WD nearly keeps the same. Such a choice is more physical, and the point is later than that of Lesaffre et al. (2006). In this work, we follow Chen et al. (2014) and Wu et al. (2016) to choose the point for explosive carbon ignition.

3 RESULTS

In Figs 1-3, we present a representative case in our simulations, in which a WD with an initial mass of $1.0 M_\odot$ accretes He-rich material at a rate of $1.6 \times 10^{-6} M_\odot \text{yr}^{-1}$. Fig. 1 shows the mass, the luminosity, and the radius of the WD during the accretion. It demonstrates that the helium shell burns steadily as we have expected, and the mass of the WD increases linearly with time. It is evident that the helium shell burning converts He-rich material to carbon and oxygen. The radius of the WD decreases as mass increases, consistent with the mass-radius relation of WDs.

Fig. 2 presents the evolution of central density and temperature for the accreting WD. We see that the density and the temperature increase first during the accretion. At the final stage of accretion, carbon
starts to burn, the WD expands (the central density drops), and finally the central density nearly keeps the same but the central temperature increases quickly, which leads to the rapid growth of the carbon burning rate at the center. In our simulations, we choose the dot in Fig. 2 as the starting point of explosive carbon burning, and it is later than what was used in Lesaffre et al. (2006) (the cross in Fig. 2).

We present the profiles of the mass fractions of helium, carbon, and oxygen of the WD at the moment just before the explosion (i.e., before the explosive ignition point) in panels (a) and (b) of Fig. 3. The accreted helium shell burns into carbon and oxygen, and this leads to the growth of the WD core. Besides, similar to the results in Cui et al. (2018), helium steady burning also leads to a higher carbon mass fraction. Panel (c) shows the profiles of elements and convection region just at the moment of carbon explosion (i.e., at the explosive ignition point). We see the boundary of the convective core reaches to about $1.2 \ M_\odot$. After testing different initial WD masses and accretion rates, we find that the boundary of convective core keep the same.

Fig. 4 shows the evolution of the carbon fraction for accreting WDs with initial masses of 0.9, 1.0 $M_\odot$ and different accretion rates. Here the carbon fraction is defined as the ratio of the total carbon mass to the total mass of the WD. We see that carbon fraction become higher during accretion since helium shell burning results in a higher carbon mass fraction than that of the initial WD. We also see that a higher accretion rate leads to a lower carbon fraction for a given WD. The reason is that the temperature of the helium shell burning region is different for various accretion rates. A higher accretion rate leads to a higher temperature, and the higher temperature leads to more oxygen gain by helium burning. Moreover, the initial WD mass has a significant influence on the C/O ratio as a lower mass CO WD has a higher C/O ratio inherently.

At the moment of explosion, a convection region of $1.2 \ M_\odot$ is developed (see panel c of Fig. 3), and the explosive ignition is at the center. We define the carbon fraction in the convection region of the WDs at the moment of the explosion as the ratio of the total carbon mass in the region to the total mass in the region. In Fig. 5, we present the carbon fractions of WDs and the carbon fractions in the convection regions at the moment of the explosion for a range of initial WD masses and different accretion rates.
Fig. 3  The chemical profile of the accreting WD just before the explosion (panels a, b) and at the moment of the explosion (panel c). The filled area is for the convective region.
We find that the carbon fractions and hence the C/O ratios\(^1\) increases with either a decreasing initial WD mass or a decreasing accretion rate.

4 DISCUSSIONS

In this work, we investigated the C/O ratio of CO WDs during the process of helium accretion. By adopting the accretion rates of Wang et al. (2015, 2017) for steady helium shell burning, we simulate the accretion of He-rich material onto WDs. We find that the C/O ratio changes with different initial WD masses and different accretion rates. In particular, both a lower initial WD mass and a lower accretion rate result in a higher C/O ratio.

A low mass CO WD tends to result from a low mass AGB star, and this will lead to a higher initial C/O ratio of the WD. Similarly, a lower accretion rate also leads to a higher C/O ratio. The reason is that the C/O ratio depends on the temperature and the density of helium burning region. As an example, Fig. 6 shows the temperature of the helium burning region for a 1.1\(M_\odot\) WD under different accretion rates during the evolution. When helium burning starts, both 3\(\alpha\) reaction for C production and 4\(\alpha\) reaction for O production occurs. The nuclear reaction rate for 4\(\alpha\) reaction increases faster than that for 3\(\alpha\) with the increase of temperature (Duorah & Kushwaha 1963). Consequently, a higher temperature for the helium burning region leads to more oxygen gained (i.e., lower C/O ratio).

We have only simulated the steady burning region of He-accreting CO WDs. But if the accretion rate is relatively low, the helium shell would flash and the mass retention efficiency of the WD would be small. Therefore, the C/O ratio for WDs may be different from those of steady burning. We make a comparison in Fig. 7 for a sample of a 1.0\(M_\odot\) WD at low accretion rate\((0.9 \times 10^{-6}M_\odot yr^{-1})\). Since the calculation of helium shell flash is difficult and consume too much cpu time, we have only increased

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\(^1\) Note the sum of the carbon fraction, the oxygen fraction, the helium fraction and \(Z\) of a WD at explosion or that in the convection region is 1.0, and the helium fraction is negligible. A higher carbon fraction means a higher C/O ratio.
the WD mass to about 1.05\(M_\odot\). We can see that if the accretion rate is lower than the steady burning region, the C/O ratio would be lower because of the flash.

In our simulation, we have not considered the rotation of the WDs. If rotation is taken into account, the WD mass may exceed the Chandrasekhar mass limit (see Yoon & Langer 2004; Hachisu et al. 2012; Wang et al. 2014), which could lead to more helium shell burning and the burning region would have a lower temperature. We would, therefore, expect a higher final C/O ratio.

Fig. 5 The carbon faction of WDs (panel a) and the fraction in the convective regions (panel b) at the moment of the explosion. Different lines stand for different initial WD masses.
Fig. 6 the temperature of the helium burning region for a 1.1 $M_\odot$ WD with different accretion rate during the evolution. Panel (b) shows the detail at the beginning of the evolution, the helium may undergo several flashes before steady burning especially for the lower accretion rate.

For the standard SD model, a WD can also accrete H-rich matter from its non-degenerate donor. In this case, H-rich material is accreted onto a CO WD and the resulted hydrogen burning shell converts hydrogen to helium. The resulted helium shell underneath the hydrogen shell burns helium into carbon and oxygen, leading to the growth of the CO WD (Cui et al. 2018). Previous works have shown that the steady burning region for hydrogen is much lower than that of helium burning (e.g. Nomoto et al. 1984; Hachisu et al. 1996; Ma et al. 2013; Wang et al. 2015; Piersanti et al. 2014; Hillman et al. 2016).
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Fig. 7 Similar to Fig. 4, the comparison of carbon fraction for 1.0 $M_\odot$ WD with low accretion rate. Different line type represents different accretion rates. The accretion rate of $0.9 \times 10^{-6} M_\odot yr^{-1}$ go through the helium shell flash.

The C/O ratio for WDs accreting H-rich material may be different from that of WDs accreting He-rich material. The accretion is more complicated because of the helium shell flashes.

It has been suggested that the C/O ratio of a WD at the moment of the explosion may affect the amount of $^{56}$Ni formed during a SN Ia (Umeda et al. 1999b). Since the amount of $^{56}$Ni formed during a SN Ia explosion dominates its maximum luminosity (Arnett 1982), a higher C/O ratio for the CO WD at explosion may lead to more $^{56}$Ni formed and make the resulted SN Ia more luminous. Previous works usually use a low C/O ratio resulted from central helium burning, and the C/O ratio at explosion is often assumed to be a particular value (Umeda et al. 1999a; Höflich et al. 2010; Meng & Yang 2011). However, our study shows that the C/O ratios could be quite diverse for WDs of different initial masses and different accretion rates, which should be taken into account for future studies.

5 CONCLUSIONS

Employing MESA, we have investigated the accretion process of He-rich material onto CO WDs. We used different initial WD masses (0.8, 0.9, 1.0, 1.1$M_\odot$) and accretion rates (1.4, 1.6, 1.8, 2.0 $\times 10^{-6} M_\odot yr^{-1}$) in our simulations, and the results indicate that both a lower initial WD mass and a lower accretion rate result in a higher C/O ratio for the accreting CO WDs before their explosion. These results can be used for future explosion simulations of SNe Ia. The variation of the C/O ratio of CO WDs at the moment of the explosion may be one of the reasons for the origin of SN Ia diversity.

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