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The effects of convective overshooting on naked helium stars

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Abstract Using stellar evolutionary models, we investigate the effects of convective overshooting on naked helium stars. We find that a larger value of overshooting parameter $\delta_{\rm ov}$ results in a larger convective core, which prolongs the lifetimes of naked helium stars on the helium main sequence and leads to higher effective temperatures and luminosities. For naked helium stars with masses lower than about 0.8 $M_\odot$, they hardly become giant stars as a result of a weak burning shell. However, naked helium stars with masses between about 0.8 $M_\odot$ and 1.1 $M_\odot$ can evolve into giant branch phases, and finally become carbon oxygen white dwarfs.

Key words: stars: evolution — stars: interiors — stars: fundamental parameters

1 INTRODUCTION

Compared with normal stars, the helium fraction of naked helium stars is very copious (up to 98%) but their hydrogen is very scarce (approaching zero). Systematic investigation of the formation and evolution of naked helium stars can help us understand a great many hydrogen-deficient objects. Both subdwarf B (sdB) stars and Wolf-Rayet (WR) stars are related to naked helium stars in the field of astrophysics.

Hot subdwarfs, involving sdB, sdO and sdOB stars, are commonly believed to be hot (20 000 K $\leq T_{\rm eff} \leq$ 80 000K) and compact stars (Sargent & Searle 1968; Heber 1986; Saffer et al. 1994). The majority of hot subdwarfs in photographic surveys are sdB stars, used as a collective term for all the hot subdwarfs in our work. Owing to helium burning cores, extremely thin hydrogen envelopes ($< 0.02\,M_\odot$) and masses which are in the vicinity of 0.5 $M_\odot$, sdB stars are considered to be low-mass naked helium stars (Han et al. 2002, 2003). The sdB stars which are naked helium stars have special atmospheric helium abundance and they can explain most of the properties of elliptical galaxies with an ultraviolet upturn (Green et al. 1986; Han et al. 2007).

WR stars have different properties than other kinds of stars. They exhibit strong and broad emission lines in their spectra, overwhelmingly high luminosity ($10^5\,L_\odot \leq L \leq 10^6\,L_\odot$) and high temperature (30 000 K $\leq T_{\rm eff} \leq$ 140 000 K) (Hamann et al. 2006). Moreover, due to strong stellar wind or high mass transfer rate in these binary systems, WR stars lose their hydrogen-rich envelopes. Therefore, they may have some relationship with naked helium stars.

One popular model supports that WR stars may be the progenitors of type Ib/c supernovae (SNe Ib/c), especially SNe Ib (Begelman & Sarazin 1986; Wheeler & Harkness 1990; van den Bergh 1992; Woosley et al. 1995). Another model suggests that SNe Ib/c may result from progenitors in close binary systems with mass transfer. In this model, SNe Ib arise from helium stars in binaries and SNe Ic are produced by carbon-oxygen stars in binaries (Nomoto et al. 1990, 1994; Dewi et al. 2002). They belong to a subclass of hydrogen-deficient SNe and result from losing the entire envelopes of stars (Van Dyk 2004). These cases are similar to naked helium stars.

In addition, SNe Ia are also related to naked helium stars. One of the reliable channels to produce SNe Ia is a binary system consisting of a carbon oxygen white dwarf (CO WD) and a helium star, in which the CO WD increases its mass to the Chandrasekhar mass by accreting material from a helium main sequence (HeMS) or a helium subgiant star (Wang et al. 2009; Wang & Han 2012).

Above all, understanding the evolution of naked helium stars is significant for developing a complete theory of stellar structure and evolution. We already know that convection can mix chemical elements in a convective region and greatly affect energy transfer in normal stars, because the size of the convective zone determines the amount of energy produced by thermonuclear reactions.

The predicted evolutionary properties of normal stars are highly sensitive to convective overshooting and this aspect has been investigated by a great number of works. Such research indicates that the larger the mass, the larger the convective zone in the center, and the more important convective overshooting is. Models with overshooting can lead to a higher surface luminosity and a wider main sequence band, and result in shrinkage of the blue loops for intermediate-mass stars and facilitate the formation of blue loops for massive stars in the Hertzsprung-Russell (H-R) diagram (Maeder & Meynet 1987, 1989; Chiosi et al. 1992; Chen & Han 2002; Jin et al. 2015).

Detailed study of the effects of convective overshooting on naked helium stars is very necessary. Hence, we investigate the evolution of naked helium stars and analyze the effects of convection and convective overshooting on naked helium stars in this work. In Section 2, we describe the model of naked helium stars. Main results and discussions are provided in Section 3. Finally, Section 4 gives conclusions.

2 MODEL

The stellar evolution code in this paper is based on Eggleton (1971, 1972, 1973) which has been updated by Han et al. (1994) and Pols et al. (1995, 1998). Pols et al. (1995) published detailed descriptions about equation of state, opacity, nuclear reaction rates and neutrino emission. The code uses a self-adaptive non-Lagrangian mesh, and in our paper, the star evolves from a zero age HeMS model. Neither stellar wind nor mass loss is included in the calculation of stellar models. The code can evolve naked helium stars with masses from 0.316 $M_\odot$ to 17.78 $M_\odot$, and here we use 499 mesh points at any stage of their evolution in our models. As for the time step, we take 10^3 years for low-mass naked helium stars ($\leq 1.1\ M_\odot$) and 10 years for massive naked helium stars ($> 1.1\ M_\odot$). Taking a naked helium star with mass of 0.4 $M_\odot$ for example, there are about 3.08×10^5 models computed in its evolution.

The initial configuration of naked helium stars is set as a homogeneous chemical composition: the helium abundance Y = 0.98, the metallicity Z = 0.02 (including the mass fractions of carbon $X_{\rm C}$ = 0.00014, nitrogen $X_{\rm N}$ = 0.01298, oxygen $X_{\rm O}$ = 0.00099, neon $X_{\rm Ne}$ = 0.00185, magnesium $X_{\rm Mg}$ = 0.00068, silicon $X_{\rm Si}$ = 0.00145 and iron $X_{\rm Fe}$ = 0.00145). We use a mixing-length parameter (the ratio of the typical mixing length to the local pressure scale height) of $\alpha_{\rm P}$ = 2.0 (Eggen 1985; Bessell et al. 1989; Pols et al. 1998).

To deal with convective overshooting, the overshooting parameter $\delta_{\rm ov}$ is used in the code. Also, mixing in a region occurs when (Schroder et al. 1997)

$$\nabla_{\rm rad} > \nabla_{\rm ad} - \nabla_{\rm ov} = \nabla_{\rm ad} - \delta_{\rm ov}/(2.5 + 20\zeta + 16\zeta^2), \tag{1}$$

where ζ is the ratio of radiation pressure to gas pressure. In addition, semiconvection happens in the inhomogeneous layer and alters the chemical composition by the condition

$$\nabla_{\rm ad} - \nabla_{\rm ov} < \nabla_{\rm rad} < \nabla_{\rm ad} - \nabla_{\rm ov} + \frac{\varphi}{\delta}\nabla_\mu, \tag{2}$$

where $\varphi \equiv (\frac{\partial \ln \rho}{\partial \ln \mu})_{\rm P,T}$, $\delta \equiv -(\frac{\partial \ln \rho}{\partial \ln T})_{\rm P,\mu}$ and ∇_μ is radial composition gradients.

We compute two cases of evolutionary models for naked helium stars with different masses: case 1 with overshooting and case 2 without overshooting. That is to say, we set $\delta_{\rm ov} = 0.0$ in case 2. According to Schroder et al. (1997), we take the parameter $\delta_{\rm ov} = 0.12$ in case 1. Correspondingly, from low-mass to massive naked helium stars, the depth of the overshooting region $d_{\rm ov}$ is from $\sim$ 0.19 $H_{\rm P}$ (pressure scale heights) to $\sim$ 0.36 $H_{\rm P}$. Figure 1 shows the behavior of the ratio of $d_{\rm ov}/r_{\rm cc}$ as a function of mass in two conditions (models at the beginning of their evolution and models when half of their central helium is left), where $r_{\rm cc}$ is the radius of the convective core.

3 RESULTS AND DISCUSSIONS

Naked helium stars are related to both sdB stars (which are $\sim$ 0.5 $M_\odot$ stars) and WR stars (which are massive stars). Both low-mass and relatively massive naked helium stars are discussed in this section.

3.1 Low-Mass Naked Helium Stars

Han et al. (2003) reported that the upper limit on mass of sdB stars might be 1.1 $M_\odot$. So, we suggest that naked helium stars with masses less than 1.1 $M_\odot$ can be called low-mass naked helium stars.

3.1.1 H-R diagram

Figure 2 shows the evolutionary tracks for naked helium stars with different masses in the H-R diagram. The star symbols on the evolutionary tracks show the point of central helium exhaustion. Our models show that naked helium stars first evolve towards the left on the H-R diagram, which is opposite to normal stars. For normal stars, lower hydrogen content in the stellar surface can lead to decreases in opacity and the star becoming bluer (Maeder & Meynet 1987). Naked helium stars have no hydrogen in our models. Therefore, their evolutionary tracks extend towards higher effective temperatures. Then by virtue of the helium shell burning, the evolution drags the models away from the area defined by sdB stars instead of reaching the asymptotic giant branch and they ultimately fade as CO WDs (Greggio & Renzini 1990; Charpinet et al. 2002). However, as mass increases, particularly greater than about 0.8 $M_\odot$, the burning helium shell becomes thicker. Accordingly, their evolutionary tracks move a bit to the right before fading as CO WDs.

As shown in Figure 2, convective overshooting results in higher effective temperatures and luminosities during the HeMS phase. The reason is that convective overshooting can provide much more fuel to the core region, weaken the discontinuity of elemental compositions nearby the convective area, and enlarge the convective zone. Subsequently, the HeMS lifetime is extended, and the rate of nuclear energy is enhanced, which increases luminosity. Just like normal stars, convective overshooting eventually widens the HeMS phase of naked helium stars.

Based on data from SDSS, Geier et al. (2015) compiled a catalog of 164 sdB stars. They listed the effective

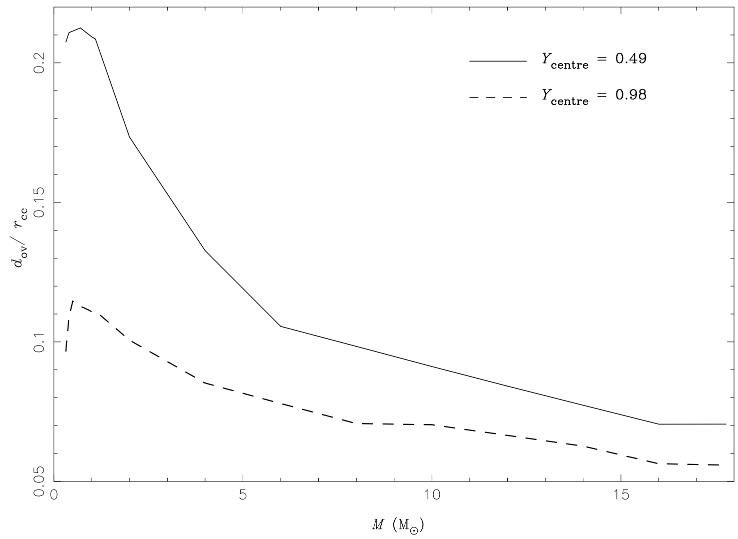

Fig. 1 The masses of naked helium stars vs. the ratios of the overshooting-region depths to the convective-core radii. The dashed line represents models at zero age on the HeMS and the solid line represents models when half of the central helium is left.

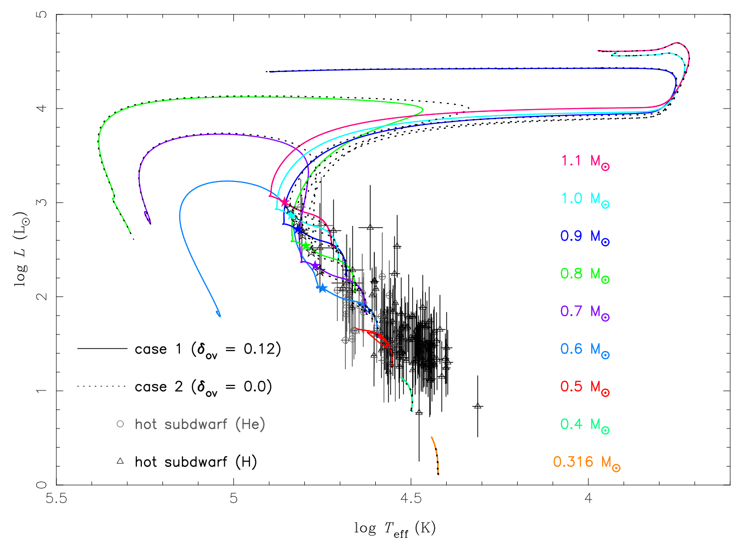

Fig. 2 Evolutionary tracks from bottom to top are for naked helium stars in the H-R diagram with masses of 0.316, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 and 1.1 $M_\odot$. The models with masses of 0.9 and 1 $M_\odot$ are terminated when the helium burning shell is unstable. For each mass there are two evolutionary tracks: the solid curve is for case 1 ($\delta_{\rm ov} = 0.12$) and the dotted curve is for case 2 ($\delta_{\rm ov} = 0.0$). The stars show the point where central helium is exhausted. The observed cases of hydrogen- and helium-rich hot subdwarfs have hydrogen and helium dominated atmospheres respectively and they are both studied by Geier et al. (2015).

temperatures and the surface gravities of these sdB stars. To locate the positions of sdB stars on the H-R diagram, we adopt the formula for luminosity as derived from gravity g and effective temperature $T_{\rm eff}$ in Edelmann et al. (2003)

$$L/L_{\rm e} = T_{\rm eff}^4/(10^{15.118} \times g), \tag{3}$$

where $L_{\rm e}$ is the Eddington luminosity which is given by

$$\begin{aligned} L_{\rm e} &= 4\pi {\rm G} M m_{\rm p} {\rm c}/\sigma_{\rm T} \\ &\cong 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right) {\rm erg\ s^{-1}} \\ &= 3.3 \times 10^4 \left(\frac{M}{M_\odot}\right) L_\odot. \end{aligned} \tag{4}$$

Here $m_{\rm p}$ is the mass of a proton, c is the speed of light and $\sigma_{\rm T}$ is the Thomson cross section. Following Han et al. (2003), we assume that all of their masses have a range from 0.3 $M_\odot$ to 0.8 $M_\odot$. Hence, the assumed mass uncertainty produces errors in the luminosities of the observational data. We can derive that the evolutionary tracks in our models can cover most helium-rich sdB stars while the majority of hydrogen-rich sdB stars are in the region more towards the right. There are three main reasons. The first is that there is no hydrogen shell in our model, which results in higher effective temperature. The second is that the effective temperature of a naked helium star is also affected by metallicity. High metallicity can increase the opacity in

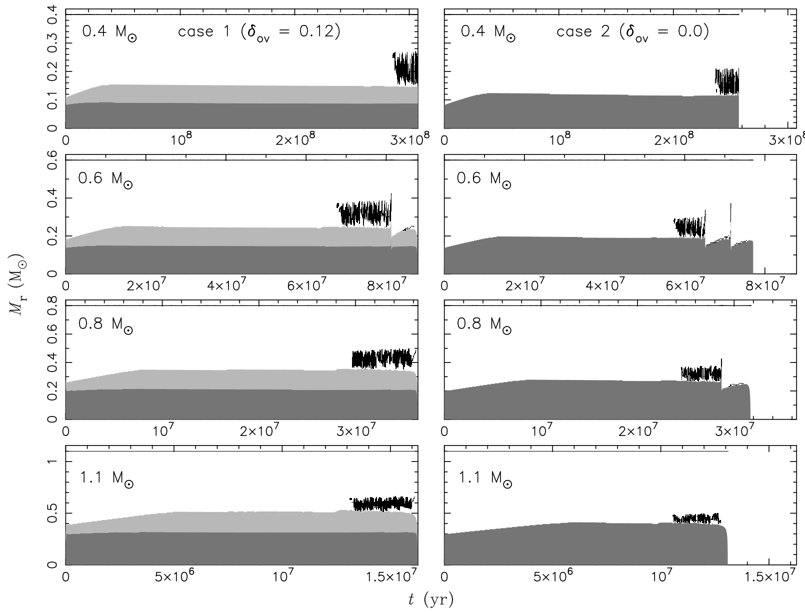

Fig. 3 The variation with time of the convective region before the exhaustion of central helium for naked helium stars with masses of 0.4, 0.6, 0.8 and 1.1 $M_\odot$. For all cases, the thin region near the stellar surface corresponds to sub-surface convection zones; the convective core is represented by dark grey, while convective overshooting is shown as light grey; the black region represents the semiconvection zone.

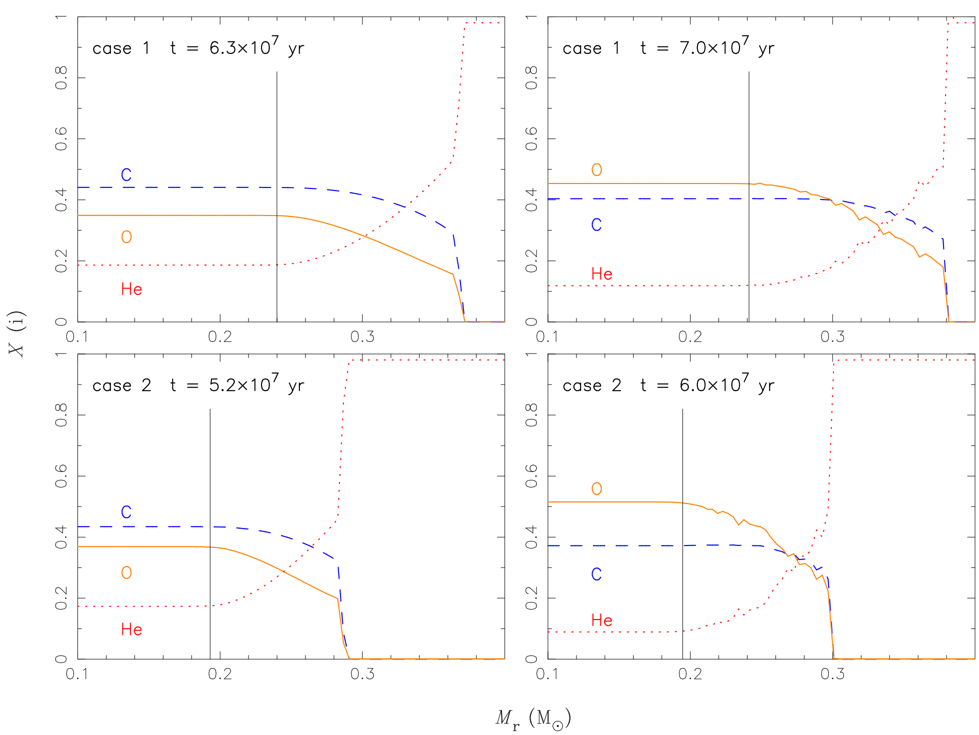

Fig. 4 The helium, carbon and oxygen profiles near the convective core before semiconvection (*left* side) and during semiconvection (*right* side) for naked helium stars with mass of 0.6 $M_\odot$ in the two cases that we consider. The vertical line represents the boundary of the convective core of the model.

the stellar models and increase the radius, hence the effective temperature would decrease. Unfortunately, the metallicities of the observed sdB stars are unknown. They are possibly very different, but we only simulate the naked helium stars with a certain metallicity ($Z = 0.02$). The third is that the formation channels of sdB stars have great effects on the properties of sdB stars (Han et al. 2002, 2003).

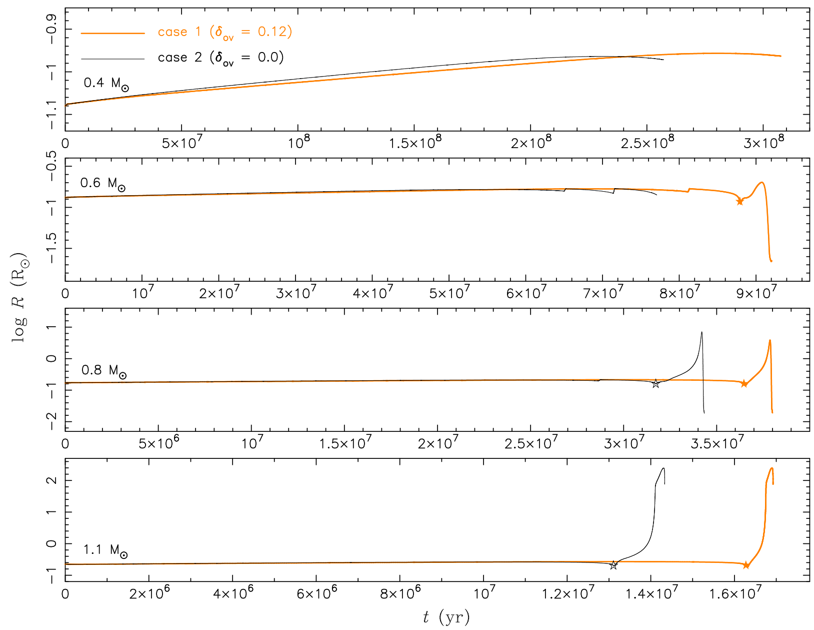

Fig. 5 The variation with time of the radius for naked helium stars with masses of 0.4, 0.6, 0.8 and 1.1 $M_\odot$, from top to bottom respectively. The orange line refers to case 1 and the black line refers to case 2. The star symbols mark the point where central helium is exhausted.

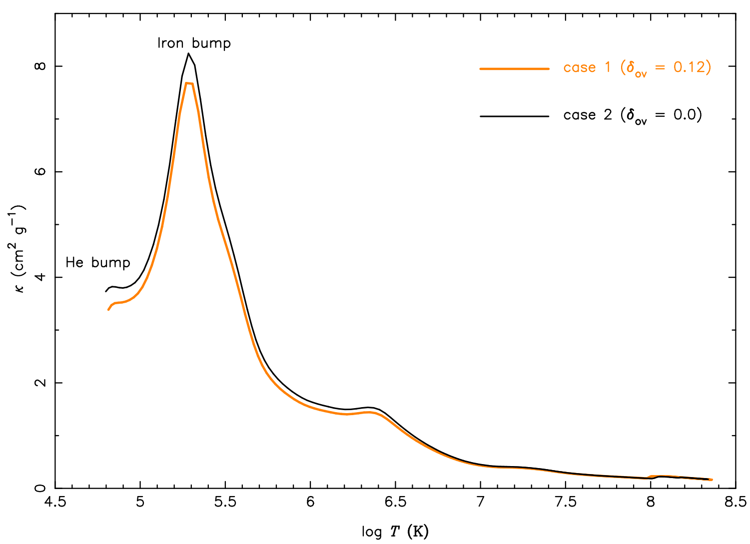

Fig. 6 When central helium is exhausted, the opacity in the interior of naked helium stars with mass of 0.8 $M_\odot$ as a function of temperature, from the surface to the inside. The orange line refers to case 1 and the black line refers to case 2.

3.1.2 Convective zone

Figure 3 displays representations of the interior structures of naked helium stars with masses of 0.4, 0.6, 0.8 and 1.1 $M_\odot$ during the HeMS phase. We can see that convective overshooting prolongs the phase of central helium burning and lengthens the lifetime. Maeder & Meynet (1987) reported that the lifetime strongly relies on the ratio of the available fuel reservoir $q_{\rm cc}M$ to luminosity L, where $q_{\rm cc}$ is the initial core mass fraction. The results of our models with overshooting have bigger convective cores than those without overshooting. Therefore, convective overshooting increases the lifetime of naked helium stars in the HeMS phase.

As central helium is exhausted, the convection will stop in their cores and the masses of the convective cores go to zero. We note that there are some unstable convective zones above the convective core near the end of the HeMS phase in our models. The reason is that before the central helium is depleted, there is a sharp chemical discontinuity in the external zone of the convective core. As most of the helium is depleted through the associated ther-

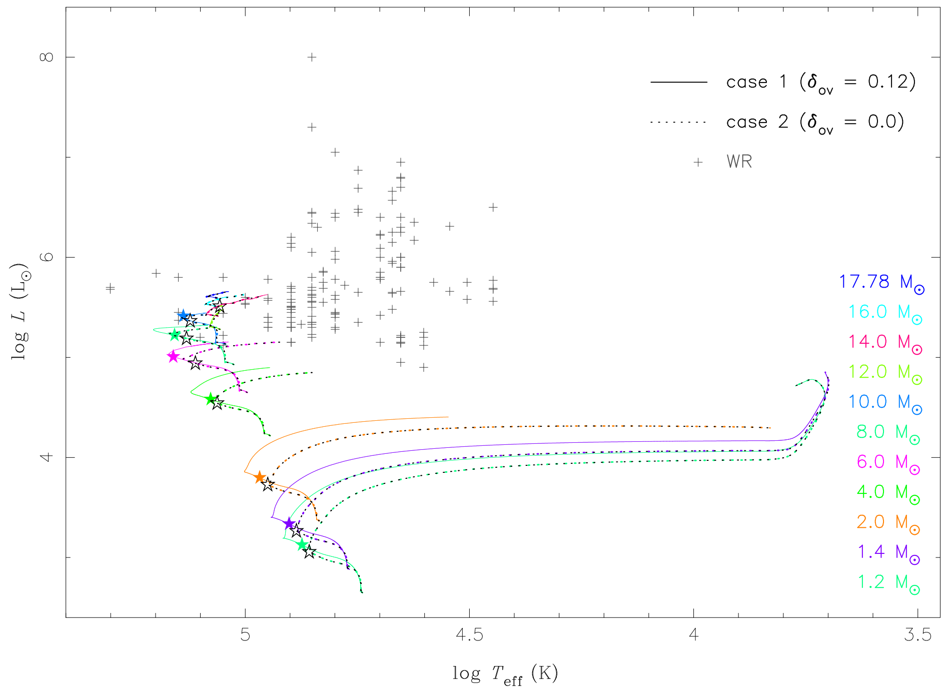

Fig. 7 Evolutionary tracks from bottom to top are for naked helium stars with masses of 1.2, 1.4, 2.0, 4.0, 6.0, 8.0, 10.0, 12.0, 14.0, 16.0 and 17.78 $M_\odot$ in the H-R diagram. The data on Galactic WR stars are taken from Hamann et al. (2006) and Sander et al. (2012).

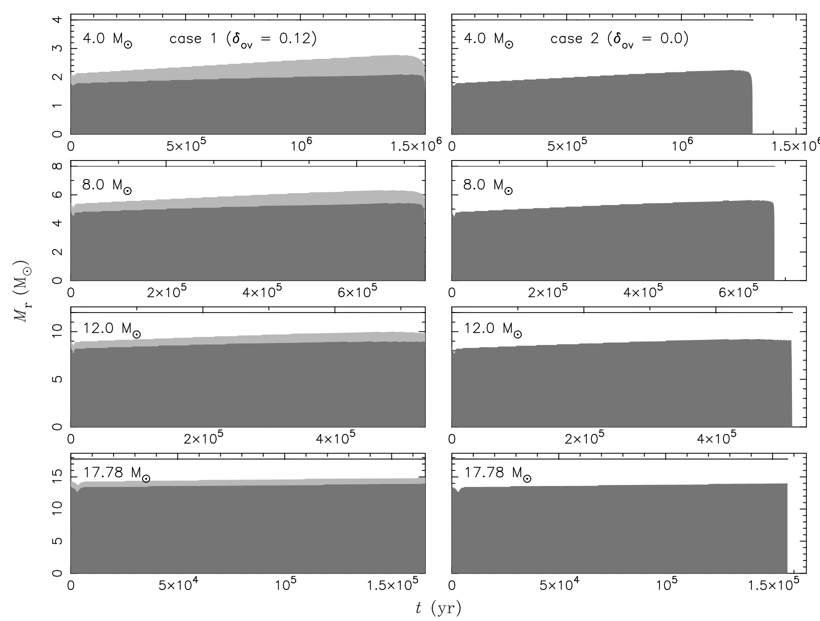

Fig. 8 The variation with time of the convective region before the exhaustion of central helium for naked helium stars with masses of 4.0, 8.0, 12.0 and 17.78 $M_\odot$, from top to bottom respectively. For all cases 1, the convective core includes the dark grey convective zone and the light grey convective overshooting region. For all cases 2, the dark grey zone represents the convective core.

monuclear reaction, abundant carbon and oxygen are generated. Figure 4 displays the helium, carbon and oxygen profiles near the convective core before the semiconvection and during the semiconvection for naked helium stars with mass of 0.6 $M_\odot$ for both cases 1 and 2. When the helium abundance is about 0.1, the burning in our models mainly occurs through reactions with carbon and helium nuclei that generate oxygen (Castellani et al. 1985). Then the opacity increases (see fig. 2 in Castellani et al. 1985), with the result that a radiative-temperature gradient becomes unstable (the region with saw-toothed chemical discontinuity). It results in the semiconvection which even induces the phenomenon of 'breathing pulses' that drive fresh helium into the region and dilutes the carbon and oxygen in the region (Castellani et al. 1971, 1985).

From Figures 3 and 4, we can find that the models with convective overshooting have a larger semiconvective region than models without overshooting. The main reason is that the convective overshooting results in a larger convective core and enlarges the region with chemical discontinuity. For models with masses of 0.6 and 0.8 $M_\odot$, the phenomenon of 'breathing pulses' occurs and the models with overshooting can weaken this phenomenon. This is because convective overshooting leads to an extensive semiconvective region which weakens the chemical discontinuity and dampens the instability surrounding the region (Castellani et al. 1985; Han et al. 2002).

In addition, we can notice that all these naked helium stars have a thin convective region in their outer envelope. It is caused by opacity peaks associated with iron and helium ionization. These convective regions are called subsurface convective zones, which also appear in hot massive normal stars (Cantiello et al. 2009).

3.1.3 Stellar radius

Figure 5 shows variations in the radius R (in solar units) of naked helium stars with time. The naked helium stars with convective overshooting in case 1 have longer HeMS lifetimes than those without convective overshooting in case 2. However, their radii are almost equal at the same evolutionary phase. The radius of a naked helium star is related to the equilibrium between radiation pressure and gravitation. The strength of gravitation is related to stellar mass. Because there is no mass loss in our model, gravitation almost does not change. Convective overshooting provides much more available nuclear fuel for the helium burning core, which increases not only the luminosity but also the temperature of naked helium stars. Figure 6 shows the variation of the opacity with temperature for two cases of a naked helium star with mass of 0.8 $M_\odot$ at the point when central helium is exhausted. According to Figure 6, we can find that the opacity in the model with convective overshooting decreases. Although convective overshooting enhances stellar luminosity, it decreases the opacity. Therefore, the radiation pressure may stay almost constant. The radius of the model is quantitatively insensitive to convective overshooting.

When the core helium is exhausted, the evolutions of naked helium stars with different masses are different. The helium-shell burning of naked helium stars with mass of 0.6 $M_\odot$ is very weak. The radius of the naked helium star decreases rapidly and the star hardly enters the giant branch. For naked helium stars with masses of 0.8 $M_\odot$ and 1.1 $M_\odot$, the helium shells are efficient, and their radii are greatly enhanced. They become helium giant stars. However, their carbon core cannot be ignited, and they terminate their life as WDs.

Figure 5 also indicates that convective overshooting weakens the phenomenon of 'breathing pulses' in the late stage of central helium depletion (Castellani et al. 1985; Han et al. 2002), especially for naked helium stars with masses of 0.6 $M_\odot$.

3.2 Relatively Massive Naked Helium Stars

Han et al. (1994) suggested that the maximum mass of a degenerate CO core is about 1.1 $M_\odot$ for a star with an initial mass less than 8 $M_\odot$. Our model with mass of 1.1 $M_\odot$ can evolve to a helium giant which has a degenerate CO core with a mass of about 1.1 $M_\odot$. Here, we discuss massive naked helium stars with mass greater than 1.1 $M_\odot$.

3.2.1 H-R diagram

Figure 7 shows the evolutionary tracks of relatively massive naked helium stars. Just like low-mass naked helium stars, these stars start to evolve towards higher effective temperatures during the HeMS phase. Owing to helium shell burning, the evolutionary path then shifts to lower effective temperatures. Since the results of models with convective overshooting increase the amount of available nuclear fuel, both the temperatures and luminosities in case 1 are higher than those in case 2.

Having utilized the WR catalog from van der Hucht (2001, 2006), Hamann et al. (2006) and Sander et al. (2012) calculated some properties of these WR stars (including the hydrostatic surface temperatures and luminosities). For simplification, we take the hydrostatic surface temperatures as the effective temperatures of the WR stars. These observed WR stars are plotted by pluses in Figure 7. Yoon et al. (2010, 2012) and Yoon (2015) studied progenitor stars of SNe Ib/c, and they found SNe Ib/c and WR stars were all related to massive naked helium stars. Very recently, McClelland & Eldridge (2016) used the model of naked helium stars to investigate the evolution of WR stars. As Figure 7 shows, the evolutionary tracks of massive naked helium stars tend to be in the area where WR stars are located.

3.2.2 Convective zone

Figure 8 presents the evolutions of convective regions of massive naked helium stars as a function of time. Similarly to low-mass naked helium stars, the convective overshooting enhances the core mass, and prolongs the lifetime of stars in the HeMS phase. The very thin sub-surface convective zone also appears in massive naked helium stars. Because the outer envelope of massive naked helium stars has a higher temperature than that of low mass naked helium stars, the sub-surface convective zone is mainly due to the iron opacity peak around $\log T \simeq 5.3$ (Cantiello et al. 2009).

4 CONCLUSIONS

In this paper, we demonstrate some properties of two different values of convective overshooting parameter $\delta_{\rm ov}$ that act upon low-mass and relatively massive naked helium stars. We find that a larger value of overshooting parameter $\delta_{\rm ov}$ results in a larger convective core, which prolongs the lifetimes of naked helium stars on HeMS and leads to higher effective temperatures and luminosities. However, the effect of convective overshooting on the radius of naked helium stars is very weak. For low-mass naked helium stars ($< 1.1\ M_\odot$), semiconvection is unstable out of the convective core, which even induces the phenomenon of 'breathing pulses' at the end of the central helium burning phase, and convective overshooting can weaken this disordered behavior. For naked helium stars with masses lower than about 0.8 $M_\odot$, they hardly become giant stars on account of weak shell burning. The naked helium stars with masses between about 0.8 $M_\odot$ and 1.1 $M_\odot$ can evolve into the giant branch, and finally become CO WDs.

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