Vol 17 No 4, April 2008
1674-1056/2008/17(04)/1518-08

Chinese Physics B

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The lack of carbon stars in the Galactic bulge*

Zhu Chun-Hua(朱春花)[a)b)], Lü Guo-Liang(吕国梁)[b)],
Wang Zhao-Jun(王兆军)[b)], and Zhang Jun(张 军)[b)†]

[a)] *School of Science, Xi'an Jiaotong University, Xi'an* 710049, *China*
[b)] *Department of Physics, Xinjiang University, Wulumuqi* 830046, *China*

(Received 29 August 2007; revised manuscript received 3 December 2007)

In order to explain the lack of carbon stars in the Galactic bulge, we have made a detailed study of thermal pulse-asymptotic giant branch (TP-AGB) stars by using a population synthesis code. The effects of the oxygen overabundance and the mass loss rate on the ratio of the number of carbon stars to that of oxygen stars in the Galactic bulge are discussed. We find that the oxygen overabundance which is about twice as large as that in the solar neighbourhood (close to the present observations) is insufficient to explain the rareness of carbon stars in the bulge. We suggest that the large mass loss rate may serve as a controlling factor in the ratio of the number of carbon stars to that of oxygen stars.

Keywords: carbon stars, thermal pulse-asymptotic giant branch (TP-AGB), population synthesis, Galactic bulge

PACC: 9700, 9720L

1. Introduction

Stars with initial masses in a range of $0.9M_{\odot} < M < 8M_{\odot}$ go through the asymptotic giant branch (AGB) phase at the end of their life. An AGB star has two nuclear burning shells: one is the burning helium surrounded a carbon–oxygen core, and the other is the burning hydrogen which is below a deep convective envelope. There exists an intershell region between helium burning shell and hydrogen burning shell. This region is rich in helium and carbon but has little neon and oxygen.[1] There are two special features in AGB evolution: thermal pulse (TP) and mass loss.[2,3] In each TP, the outer layers expand due to the high helium burning luminosity. The strong expansion has an influence on extinguishing the hydrogen shell. Then the deep convective envelope can penetrate into the intershell region and mix with the products of internal nucleosynthesis. This mixing event is named the third dredge up (TDU). Following the dredge up, the hydrogen shell is re-ignited due to the star contraction. The star enters a phase of quiescent hydrogen burning known as the interpulse phase. In the current understanding of the stellar evolution theory, the carbon stars cannot be formed before the TP-AGB phase, the phase which occurs after the first TP to the end of AGB. After each TP, the surface abundances of TP-AGB stars may be modified by the TDU.[4] Following the dredge up, a certain quantity of intershell matter is brought up to the surface, and the surface abundance of ^{12}C becomes enriched. Under the repeated actions of TPs and TDUs, the stars can become carbon stars with ratio C/O > 1 in the envelopes if they are efficient enough. In recent decades, many studies have shown that the carbon stars in the Galactic bulge are very rare as compared with the numbers in the solar neighbours.[5,6] The recent study[7] has indicated that the stellar population of the Galactic bulge does not contain any normal carbon stars except one candidate. However, the rareness of the bulge carbon stars is still a mystery. Feast[7] showed the lack of carbon stars in the bulge could not be explained simply by an age effect or a high metal abundance and suggested that the oxygen overabundance maybe modified the ratio of the number of carbon stars to that of oxygen giants.

In this paper, using the synthetic models and the different parameters of the initial oxygen abundance, we simulate TP-AGB stars in the Galactic bulge and discuss the effect of oxygen overabundance on the ratio

*Project supported by the National Natural Science Foundation of China (Grant No 10647003), and the Foundations of Xinjiang University, China (Grant Nos 070195 and BS060109).
†Corresponding author. E-mail: zhj@xju.edu.cn

of the number of carbon stars to that of oxygen TP-AGB stars (O-rich stars). In addition, we attempt to find the other controlling factors in the ratio of the number of carbon stars to that of O-rich stars, for example, the mass loss. In Section 2, we present our assumptions and describe some details of the algorithm. In Section 3, we discuss the main results and the effects of the different parameters. In Section 4, the main conclusions are given.

2. The model

2.1. Basic parameters of the Monte Carlo simulation

For the population synthesis of the single stars, the main input parameters of the model are: i) the initial mass function (IMF); ii) the lower and the upper mass cut-offs $M_{\rm l}$ and $M_{\rm u}$ for the initial mass function; iii) the relative age of the single stellar population; iv) the metallicity Z of the star.[8−10]

Our primary mass distribution takes the IMF as[11]

$$\xi(m)\mathrm{d}m = \begin{cases} 0 & m \le m_0, \\ a_1 m^{-1.3}\mathrm{d}m & m_0 < m \le 0.5, \\ a_2 m^{-2.2}\mathrm{d}m & 0.5 < m \le 1.0, \\ a_2 m^{-2.7}\mathrm{d}m & 1.0 < m < \infty, \end{cases} \quad (1)$$

where $\xi(m)\mathrm{d}m$ is the probability with which a star has a mass (in solar units) between m and $m + \mathrm{d}m$; $m_0 = 0.1M_\odot$; $a_1 = 0.29056$; $a_2 = 0.15571$.

The lower and the upper mass cut-offs are $M_{\rm l} = 0.1M_\odot$ and $M_{\rm u} = 120M_\odot$, respectively. If the initial mass is larger than $4.0M_\odot$, the stars hardly become carbon stars because of the hot bottom burning which turns ^{12}C into ^{14}N. At the same time, the absence of the TDU prevents the carbon star from forming when the initial mass is less than $1.5M_\odot$. Therefore, we lay a strong emphasis on the stars with the initial masses ranging from $1.5M_\odot$ to $4.0M_\odot$ in this paper.

The average value of [Fe/H] in the Galactic bulge is close to the mean value for the solar neighbourhood.[12] In our work, we take the metallicity as $Z = 0.02$ for convenience. The maximum age of the single stellar population is 15 Gyr.

The recent work has shown that the star formation rate in the Galactic bulge is $10 - 100M_\odot$ yr^{-1}.[13,14] We assume that the stars with total mass of about $50M_\odot$ are born in the bulge every year.

2.2. Synthesized TP-AGB evolution

The stellar evolution from the zero age main sequence to the first thermal pulse is dealt with using the rapid evolution code by Hurley *et al.*[15] After the first thermal pulse, we use a synthetic model for TP-AGB. The changes of the chemical abundances on the stellar surface during the giant branch (the first dredge up) and the early AGB (E-AGB) phase (the second dredge up) can be represented by the simple fitting formulae in Refs.[16, 17]. In the following sections, the fitting formulae mainly come from Refs.[16, 17]. They are comprised of a Levenberg–Marquart gradient descent iterative χ^2-minimization code.[16]

2.2.1. The initial abundances

It has been known that oxygen in the bulge M giants is overabundant about twice larger than that in the solar neighbourhood.[18] In our work, we take the initial abundances as those in Ref.[19] for $Z = 0.02$ except oxygen abundance. To study the effect of the oxygen overabundance on the ratio of the number of carbon stars to that of O-rich stars, the oxygen overabundance is taken as the corresponding value of coefficient θ in each case involved in our model. The details are shown in Table 1. The following data are the initial abundances shown by the mass fractions in our model:

^{1}H=0.68720, ^{4}He=0.29280,
^{12}C=2.92293×10^{-3}, ^{13}C=4.10800×10^{-5},
^{14}N=8.97864×10^{-4}, ^{15}N=4.14000×10^{-6},
^{16}O=8.15085×10^{-3} × θ, ^{17}O=3.87600×10^{-6},
^{20}Ne=2.29390 ×10^{-3}, ^{22}Ne=1.45200×10^{-4}.

The data for other elements are not shown here, and they do not affect our results. The enrichment of ^{16}O is equivalent to the enhancements of α elements which change the stellar opacity. Then, the enrichment of ^{16}O may have some influence on the stellar evolution.

Table 1. Parameters of the models. θ means the coefficient of oxygen overabundance.

case	coefficient θ	Mass loss rate
case 1	1.0	Eq.(9)
case 2	2.0	Eq.(9)
case 3	3.0	Eq.(9)
case 4	5.0	Eq.(9)
case 5	2.0	Eq.(12)
case 6	5.0	Eq.(12)

Salasnich *et al*[20] have shown that the enhancements of α elements have a very small influence on the evolution of the low mass stars ($M < 5M_{\odot}$). The carbon stars originate from the stars with masses lower than $4M_{\odot}$. In our paper, we neglect the influence of the enrichment of ^{16}O on the stellar evolution. While the abundance of ^{16}O increases, we divide all metal element abundances by $\frac{0.02+(\theta-1)^{16}\mathrm{O}}{0.02}$ in order to keep $Z = 0.02$, where $^{16}\mathrm{O} = 8.15085 \times 10^{-3}$.

2.2.2. Core mass during the first thermal pulse

Using the rapid evolution code by Hurley *et al*,[15] we can obtain the stellar mass ($M_{1\mathrm{TP}}$) during the first thermal pulse. The core mass during the first thermal pulse, $M_{\mathrm{c,1TP}}$, is[1]

$$M_{\mathrm{c,1TP}} = [-p_1(M_0 - p_2) + p_3]f + (p_4 M_0 + p_5)(1 - f), \quad (2)$$

where $f = \left(1 + \mathrm{e}^{\left(\frac{M_0 - p_6}{p_7}\right)}\right)^{-1}$, and M_0 is the initial mass in solar units. The coefficients p_1, p_2, p_3, p_4, p_5, p_6 and p_7 are shown in Table 6 of Ref.[1].

2.2.3. Luminosity, radius and interpulse period

We use the prescriptions by Izzard *et al.*[16] The luminosity is taken as the value calculated from Eq.(29) in Ref.[16]. We define radius R as $L = 4\pi\sigma R^2 T_{\mathrm{eff}}^4$, where σ is the Stefan–Boltzmann constant and T_{eff} is the effective temperature of the star. The radius is taken as the value calculated from Eq.(35) in Ref.[16]. The interpulse period τ_{ip} is

$$\lg(\tau_{\mathrm{ip}}/\mathrm{yr}) = a_{28}(M_{\mathrm{c}}/M_{\odot} - b_{28}) - 10^{c_{28}} - 10^{d_{28}} + 0.15\lambda^2, \quad (3)$$

where the TDU efficiency λ is defined in Section 2.2.4, and the coefficients are

$$a_{28} = -3.821,$$
$$b_{28} = 1.8926,$$
$$c_{28} = -2.080 - 0.353Z + 0.200(M_{\mathrm{env}}/M_{\odot} + \alpha - 1.5),$$
$$d_{28} = -0.626 - 70.30(M_{\mathrm{c,1TP}}/M_{\odot} - \zeta)(\Delta M_{\mathrm{c}}/M_{\odot}),$$

where M_{env} represents the envelope mass, α is the mixing length parameter and equal to 1.75, $\zeta = \log(Z/0.02)$, and ΔM_{c} is the change in core mass defined as $\Delta M_{\mathrm{c}} = M_{\mathrm{c}} - M_{\mathrm{c,1TP}}$.

2.2.4. The minimum core mass for the TDU and the TDU efficiency

The TDU can occur only in stars with masses above a certain core mass $M_{\mathrm{c}}^{\mathrm{min}}$. Groenewegen and de Jong took $M_{\mathrm{c}}^{\mathrm{min}}$ as a constant $0.58M_{\odot}$.[21] Karakas *et al*[1] have found that $M_{\mathrm{c}}^{\mathrm{min}}$ depends on the stellar mass and the metallicity. They gave a fitting formula

$$M_{\mathrm{c}}^{\mathrm{min}} = a_1 + a_2 M_0 + a_3 M_0^2 + a_4 M_0^3, \quad (4)$$

where coefficients a_1, a_2, a_3 and a_4 are shown in Table 7 of Ref.[1] and M_0 is the initial mass in solar units. According to the carbon star luminosity function in the Magellanic clouds, Marigo and Girardi[22] have considered that the predicted $M_{\mathrm{c}}^{\mathrm{min}}$ in Ref.[1] is high. In this work, we take the value calculated from Eq.(4) as $M_{\mathrm{c}}^{\mathrm{min}}$.

It should be recalled that $M_{\mathrm{c}}^{\mathrm{min}} = M_{\mathrm{c,1TP}}$ if a stellar initial mass is $M_{\mathrm{initial}} \geq 4M_{\odot}$ or $M_{\mathrm{c}}^{\mathrm{min}} < M_{\mathrm{c,1TP}}$.[1,16]

The TDU efficiency is defined as $\lambda = \frac{\Delta M_{\mathrm{dred}}}{\Delta M_{\mathrm{H}}}$, where ΔM_{dred} is the mass dredged up to the stellar surface during the thermal pulse, and ΔM_{H} is an increment of the core mass due to hydrogen burning during the preceding interpulse period. λ is a very uncertain parameter. Karakas *et al*[1] showed a relation of λ to be

$$\lambda(N) = \lambda_{\mathrm{max}}[1 - \exp(-N/N_{\mathrm{r}})], \quad (5)$$

where λ gradually increases towards an asymptotic λ_{max} with the increase of N (the progressive number of thermal pulsation), and N_{r} is a constant determining how fast λ reaches λ_{max}. In our work, N_{r} is taken as the value calculated from Eq.(49) in Ref.[16], which can reproduce the results for N_{r} in Table 5 of Ref.[1]. λ_{max} is given by (see Eq.(6) in Ref.[1])

$$\lambda_{\mathrm{max}} = \frac{b_1 + b_2 M_0 + b_3 M_0^3}{1 + b_4 M_0^3}, \quad (6)$$

where coefficients b_1, b_2, b_3 and b_4 are shown in Table 8 of Ref.[1].

In this paper, we take λ as the value calculated from Eq.(5).

2.2.5. Intershell abundances

During the every thermal pulse, the dredged mass ΔM_{dred} incorporates into stellar envelope. According to the nucleosynthesis calculations by Boothroyd and Sackmann,[23] Marigo and Girardi[22] gave the fitting

of the abundances of ^{4}He, ^{12}C and ^{16}O in the inter-shell region which lies between helium burning shell and hydrogen burning shell:

for $\Delta M_{\rm c} \leq 0.025 M_\odot$,
$^{\rm inter}X(^4{\rm He}) = 0.95 + 400(\Delta M_{\rm c})^2 - 20.0\Delta M_{\rm c}$,
$^{\rm inter}X(^{12}{\rm C}) = 0.03 - 352(\Delta M_{\rm c})^2 + 17.6\Delta M_{\rm c}$,
$^{\rm inter}X(^{16}{\rm O}) = -32(\Delta M_{\rm c})^2 + 1.6\Delta M_{\rm c}$,
for $\Delta M_{\rm c} > 0.025 M_\odot$,
$^{\rm inter}X(^4{\rm He}) = 0.70 + 0.65(\Delta M_{\rm c} - 0.025)$,
$^{\rm inter}X(^{12}{\rm C}) = 0.25 - 0.65(\Delta M_{\rm c} - 0.025)$,
$^{\rm inter}X(^{16}{\rm O}) = 0.02 - 0.065(\Delta M_{\rm c} - 0.025)$.

All the other isotopes are set to be zero in the inter-shell region and the abundances are renormalized such that their sum is 1.0.

2.2.6. The third dredge up and the hot bottom burning

If the hydrogen envelope of an AGB star is sufficiently massive, the hydrogen burning shell can extend to the bottom of the convective region. This process is named the hot bottom burning (HBB). For the HBB, we use a treatment similar to that in Ref.[21]. According to the model by Iben and Renzini,[24] Groenewegen and de Jong[21] gave the most suitable parameters for the fraction of newly dredged up matter exposed to high temperatures at the bottom of the envelope $f_{\rm HBB} = 0.94$, the fraction of the envelope matter mixed down with the bottom of the envelope $f_{\rm bur} = 3 \times 10^{-4}$ and the exposure time of the matter in the region of the HBB $t_{\rm HBB} = 0.0014\tau_{\rm ip}$. The temperature at the bottom of convective envelope $T_{\rm bce}$ is given by Eq.(37) of Ref.[16].

For the drudged up masses, the quantities of materials added to the envelope are:

$$\Delta^4{\rm He} = {}^{\rm inter}X(^4{\rm He})\Delta M_{\rm dred},$$

$$\Delta^{12}{\rm C} = \left[(1-f_{\rm HBB})^{\rm inter}X(^{12}{\rm C}) + \frac{f_{\rm HBB}}{t_{\rm HBB}}\int_0^{t_{\rm HBB}} X_{12}^{\rm HBB}(t){\rm d}t\right]\Delta M_{\rm dred},$$

$$\Delta^{13}{\rm C} = \left[\frac{f_{\rm HBB}}{t_{\rm HBB}}\int_0^{t_{\rm HBB}} X_{13}^{\rm HBB}(t){\rm d}t\right]\Delta M_{\rm dred},$$

$$\Delta^{14}{\rm N} = \left[\frac{f_{\rm HBB}}{t_{\rm HBB}}\int_0^{t_{\rm HBB}} X_{14}^{\rm HBB}(t){\rm d}t\right]\Delta M_{\rm dred},$$

$$\Delta^{16}{\rm O} = \left[(1-f_{\rm HBB})^{\rm inter}X(^{16}{\rm O}) + \frac{f_{\rm HBB}}{t_{\rm HBB}}\int_0^{t_{\rm HBB}} X_{16}^{\rm HBB}(t){\rm d}t\right]\Delta M_{\rm dred}, \quad (7)$$

where $X^{\rm HBB}(t)$ is the chemical abundance of the material undergoing the HBB, and it is calculated in the way of Clayton's CNO bicycle.[25] The details of Clayton's CNO bicycle can be seen in Ref.[25] (also see Refs.[16, 21]). The CNO bicycle can be split into the CN cycle and the ON cycle. The timescales in ON cycle are many thousands of times longer than those required to bring the CN cycle into equilibrium. Even in the most massive AGB stars undergoing vigorous HBB, the ON cycle never approaches equilibrium. Therefore, the effects of HBB mainly turn ^{12}C into ^{14}N and the abundance of ^{16}O is not changed much. In the calculation of Clayton's CNO bicycle, the density on the base of the convective envelope is given by Eq.(42) of Ref.[16] and the analytic expressions for the nuclear reaction rates in Clayton's CNO bicycle are cited from Ref.[26]. The initial conditions of $X^{\rm HBB}(t)$ are $X^{\rm HBB}(t=0) = {}^{\rm inter}X$ for ^{12}C and ^{16}O, while $X^{\rm HBB}(t=0) = 0$ for ^{13}C and ^{14}N.

After every thermal pulse, the chemical abundances of stellar envelope $X^{\rm new}$s each are

$$X^{\rm new} = \frac{X^{\rm old}M_{\rm env}(1-f_{\rm bur}) + \Delta X + \dfrac{f_{\rm bur}M_{\rm env}}{t_{\rm HBB}}\displaystyle\int_0^{t_{\rm HBB}} X(t){\rm d}t}{M_{\rm env} + \Delta M_{\rm dred}}, \quad (8)$$

where the values of ΔX are given by expression (7) and the values of initial conditions of $X(t)$ are the values of $X(t=0)$ that are equal to $X^{\rm old}$s.

In this work, we care about the ratio of the number of carbon atoms to that of the oxygen atoms on the stellar surface and denote it as C/O.

2.2.7. Mass loss

The mass loss rate of the cool giant during AGB phase has a great influence on the chemical evolution

of the stellar surface. In our work, two laws of the mass loss rate are considered:

i) A mass loss relation suggested by Vassiliadis and Wood[27] based on the observations, and it is given as

$$\log \dot{M} = -11.4 + 0.0123(P - 100 \times \max(M/M_{\odot} - 2.5, 0.0)), \quad (9)$$

where P is the Mira pulsation period in days, given by

$$\log P = -2.07 + 1.94 \log(R/R_{\odot}) - 0.90 \log(M/M_{\odot}). \quad (10)$$

When $P \geq 500$ days, the steady super-wind phase is modelled by the law

$$\dot{M}(M_{\odot}\mathrm{yr}^{-1}) = 2.06 \times 10^{-8} \frac{L/L_{\odot}}{v_{\infty}}, \quad (11)$$

where v_{∞} is the terminal speed of the super-wind in km s^{-1}; we use $v_{\infty} = 15$ km s^{-1} in this paper.

ii) A mass loss rate similar to Reimers' formula, which is given by Blöcker[28] according to the simulations of shock-driven winds in the atmospheres of Mira-like stars[29] and expressed as

$$\dot{M} = 4.83 \times 10^{-9} M^{-2.1} L^{2.7} \dot{M}_{\mathrm{Reimers}}, \quad (12)$$

where $\dot{M}_{\mathrm{Reimers}}$ is given by expression (13), and $\eta = 0.02$.[30]

In the other stellar evolutionary phases, the mass loss rate is given by Reimers' formula[31]

$$\dot{M} = -4.0 \times 10^{-13} \eta \frac{LR}{M} M_{\odot}\mathrm{yr}^{-1}, \quad (13)$$

where L, R and M are the stellar luminosity, radius and mass in solar units, respectively, and the free parameter is $\eta = 0.5$.

3. Results

We construct a set of models with different input parameters. Table 1 lists all the cases considered in the present work. We calculate 1×10^5 single stars for each case.

3.1. The effects of parameters

3.1.1. Positions in Hertzsprung–Russel (HR)-diagram

In Fig.1, the different evolutionary phases during TP-AGB in HR-diagram are shown. For the same mass loss rate (see Figs.1(a)–1(d), or Figs.1(e) and 1(f)), it is more difficult to form carbon stars with the increase of oxygen overabundance coefficient θ because the stars must drudge up more ^{12}C to the stellar surface in order to obtain C/O> 1. When $\theta = 5.0$, the initial oxygen abundance is too high so that the dredged up ^{12}C is not enough to reach C/O> 1, thus there is no carbon star (see Fig.1(d)). On the other hand, for the same coefficient θ (Figs.1(b) and 1(e), or Figs.1(d) and 1(f)), the mass loss rate taken as the value calculated from expression (9) is more favourable for preventing the carbon stars from forming than that described by Eq.(12). As we can see from Fig.1, the stars with the initial masses from $2.0M_{\odot}$ to $4.0M_{\odot}$ may become the carbon stars.

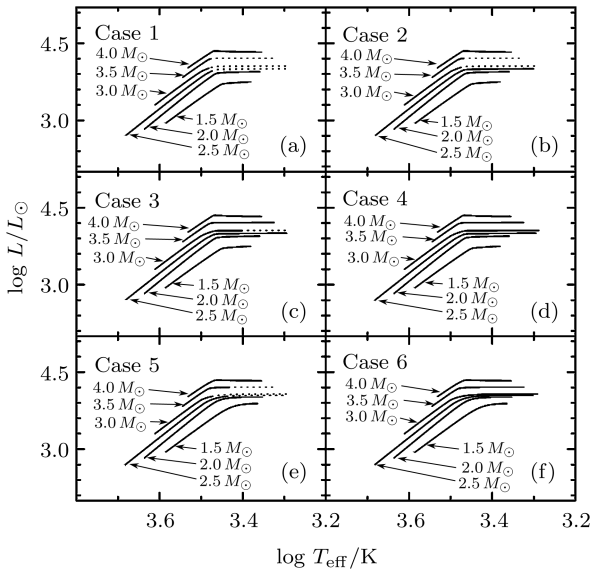


Fig.1. The positions of TP-AGB stars in HR-diagram for the different cases. The solid lines mean O-rich TP-AGB stars and the dotted lines represent carbon stars. Stellar initial masses are shown by the figures on the side of the lines.

3.1.2. Variety of C/O

Figure 2 shows the varieties of C/O during the TP-AGB phase. For a star with an initial mass of $1.5M_{\odot}$, C/O is almost a constant as shown in Fig.2(a). Figures 2(b)–2(f) show that for the stars with initial masses ranging from $2.0M_{\odot}$ to $4.0M_{\odot}$, the values of ratio C/O are all changed but their variations are different from each other. For a star with an initial mass of $2.0M_{\odot}$ (see Fig.2(b)), the core mass M_{c} is lower than $M_{\mathrm{c}}^{\mathrm{min}}$ when it just evolves to the TP-AGB. It takes a long time to satisfy a certain core mass of $M_{\mathrm{c}}^{\mathrm{min}}$ of the TDU. Therefore, it is hard to reach C/O> 1. There is no carbon star with an initial mass of $4.0M_{\odot}$

(see Fig.2(f)). The main reason is that the star with an initial mass higher than $4.0M_{\odot}$ has a convective envelope which is thick enough, thus the temperature at the bottom of the convective envelope, $T_{\rm bce}$, is high enough to undergo the HBB. The HBB turns ^{12}C in the drudge up materials into ^{14}N and prevents the carbon stars from forming.[16] From Fig.2(e), we can see obviously the largest variety of C/O in case 1 and the smallest in case 4 for the stars with the same initial masses. It means that case 4 is the most unfavorable case for forming the carbon star in our model.

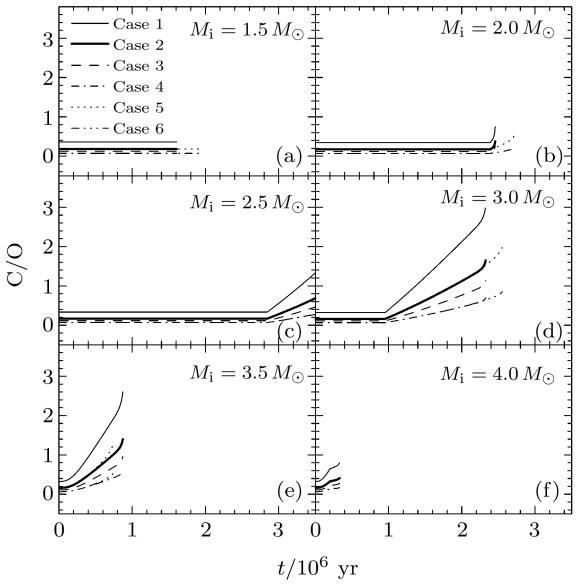


Fig.2. The varieties of C/O during the TP-AGB phase in the different cases and the initial masses. Stellar initial masses are shown in right top corners. The cases the different styles of lines correspond to are shown in the left top region of Fig.2(a).

3.1.3. Lifetimes

Figure 3 gives the stellar lifetimes of the different evolutionary phases. The phase of the carbon stars is a small fraction of the whole TP-AGB. From Fig.3, we see that the peaks of lifetimes for the carbon stars each appear at $3.1M_{\odot}$, which are different from the peaks at $2.5M_{\odot}$ for the whole TP-AGB stars. The main reason is as follows: for a star with an initial mass of $3M_{\odot}$, $M_{\rm c}^{\rm min} \simeq M_{\rm c,1TP}$ when it evolves into the TP-AGB phase. After a few thermal pulses the star begins to undergo the TDU. At the same time, according to expression (6), the $\lambda_{\rm max}$ is about 0.8 for a $3M_{\odot}$ star (also see Fig.4 of Ref.[1]). Therefore, the TDU has a high value of efficiency λ. The increases of its core mass and the mass loss of the envelope are slow so that the star takes a longer time to evolve to the end of TP-AGB.

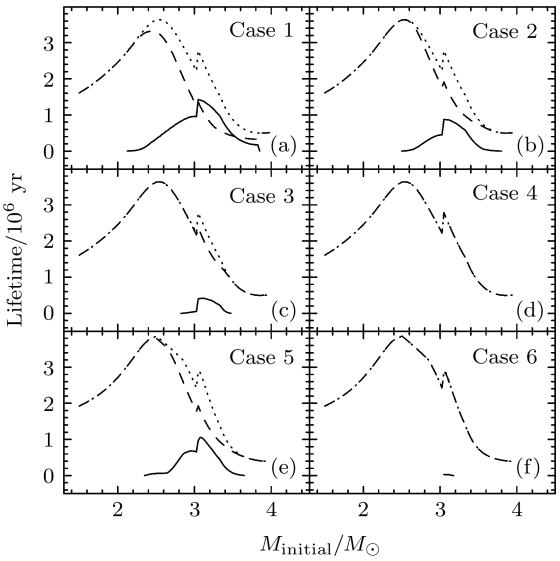


Fig.3. The stellar lifetimes of different evolutionary phases. The dot-dashed, dashed and solid lines represent the whole TP-AGB stars, O-rich stars and Carbon stars, respectively.

Figure 3 shows that the oxygen overabundance coefficient θ has a significant influence on the lifetimes of the carbon stars. With the increase of coefficient θ, the lifetimes of the carbon stars decrease. There is no carbon star when θ increases up to 5.0 (see Fig.3(d)). In addition, Fig.3 indicates that the mass loss rate also has an influence on the lifetimes of the carbon stars. For the same values of coefficient θ (Figs.3(b) and 3(e)), the lifetimes of the carbon stars with the mass loss rate as expressed by expression (9) are shorter than that given by expression (12).

3.1.4. Mass distribution

Figure 4 shows the distributions of numbers (all the numbers are normalized to 1) of the modelled TP-AGB stars in the Galactic bulge each as a function of initial stellar mass. Figure 4 shows that the initial masses of the progenitors of the carbon stars range mainly from $2.5M_{\odot}$ to $3.5M_{\odot}$ and the peaks of the initial masses of the carbon stars each appear at $3.1M_{\odot}$, which is in good agreement with the case in Fig.3. Comparing the cases in Fig.4, we easily see the effects of the parameter θ and the mass loss rate. The results are consistent with the descriptions in Fig.3.

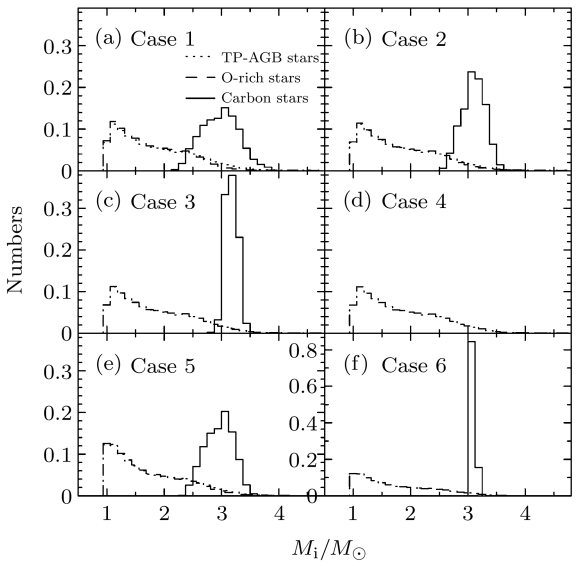


Fig.4. The distributions of numbers (all the numbers are normalized to 1) of the modelled TP-AGB stars in the Galactic bulge each as a function of initial stellar mass. The cases the different styles of lines correspond to are shown in the right top region of Fig.4(a).

3.2. Lifetimes and the numbers of carbon stars

In this subsection, we discuss the rough properties of the modelled population of carbon stars in the Galactic bulge and then proceed to make a more detailed comparison among the influences from the different assumptions.

Table 2 gives the different models of TP-AGB population in the Galactic bulge.

i) The mass loss rate is taken as the value calculated from expression (9) (cases 1, 2, 3 and 4); the numbers of the carbon stars in the bulge may range from 0 (case 4) to 6.02×10^5 (case 1). Their average lifetimes range from 0 (case 4) to 0.48×10^6 years (case 1). The ratios of the number of O-rich stars to that of the carbon stars may range from 17.3 (case 1) to ∞ (case 4), where ∞ means that there is no carbon star in this case. The above results suggest that the oxygen overabundance has a great influence on the numbers and the lifetimes of the carbon stars in the bulge. As shown in Table 2, the numbers and the lifetimes of the carbon stars decrease with coefficient θ increasing. It is worth mentioning that Rich and Origlia[18] indicated that in the bulge M giants oxygen overabundance is twice as big as that in the solar neighbourhood. According to our model, $\theta = 2.0$, which is insufficient for the lack of the carbon stars in the Galactic bulge. The carbon stars cannot form when $\theta = 5.0$ in our model, but the initial oxygen abundance is much higher than the observed one.

Table 2. The different models of TP-AGB population. The first column gives case number according to Table 1. Columns 2, 4 and 6 give the numbers of TP-AGB stars, O-rich stars and carbon stars in the bulge, respectively. Columns 3, 5 and 7 show the average lifetimes of TP-AGB, O-rich and carbon stars, respectively. Column 8 is the ratios of the number of O-rich stars to that of carbon stars.

cases	TP-AGB stars		O-rich stars		Carbon stars		the ratios
	number	lifetime	number	lifetime	number	lifetime	of the
	10^5	10^6yrs	10^5	10^6yrs	10^5	10^6yrs	number
1	2	3	4	5	6	7	8
case 1	113.23	1.46	107.03	1.38	6.20	0.48	17.3
case 2	113.23	1.46	110.94	1.43	2.28	0.29	48.7
case 3	113.23	1.46	112.59	1.45	0.63	0.17	178.7
case 4	113.23	1.46	113.23	1.46	0	0	∞
case 5	138.52	1.79	135.07	1.74	3.45	0.37	39.2
case 6	138.52	1.79	138.51	1.79	0.02	0.02	6925.5

ii) The mass loss rate is taken as the value calculated from expression (12) (cases 5 and 6): Table 2 shows that the numbers and the average lifetimes of the carbon stars may range from 0.02×10^5 (case 6) to 3.45×10^5 (case 5) and from 0.02×10^6 yrs (case 6) to 0.37×10^6 yrs (case 5), respectively. It is obvious that the oxygen overabundance is favourable for preventing the carbon stars from forming, however, it is not enough to explain the lack of carbon stars in the bulge unless the oxygen overabundance coefficient θ is equal to 5.0. This is consistent with the above result.

iii) For the same values of coefficient θ (cases 2 and 5, or cases 4 and 6), we can see from Table 2 that the mass loss rate taken as the value calculated from expression (9) is helpful for explaining the lack of the carbon stars in the Galactic bulge. Recently, Willson[32]

gave a detailed description on $\mathrm{d}(\log \dot{M})/\mathrm{d}(\log L)$ (see Fig.1 of Ref.[32]). The average mass loss rate calculated from expression (9) is higher than that calculated from expression (12) during the TP-AGB in our simulations. The higher the mass loss rate is, the more quickly the envelope mass $M_{\rm env}$ will decrease. According to expression (3), the interpulse period $\tau_{\rm ip}$ increases with envelope mass decreasing. A long $\tau_{\rm ip}$ can reduce the TDU progressive number and the value of TDU efficiency λ. The large mass loss rate is unfavorable for forming the carbon stars. The environment in the Galactic bulge is significantly different from that in the solar neighbourhood, for example, the higher irradiating luminosity and the stellar density. These factors may enhance the stellar mass loss rate. We suggest that the mass loss rate may be a factor of controlling the ratio of the number of O-rich stars to the number of carbon stars in the Galactic bulge.

4. Conclusion

Employing the population synthesis, we make a detailed study of the TP-AGB stars in the Galactic bulge. We emphasize the relationship between the formation of the carbon stars and the relevant parameters. The effects of the oxygen overabundance coefficient and the mass loss rate on the ratio of the number of the carbon stars to the that of O-rich stars are discussed. We find that the ratio of the number of the carbon stars to that of O-rich stars is greatly affected by the oxygen overabundance coefficient θ. However, from the present observations of the oxygen overabundance in the Galactic bulge, we believe that the oxygen overabundance which is about twice as large as that in the solar neighbourhood is insufficient to explain the lack of the carbon stars in the bulge. In addition, we obtain that the mass loss rate also is a controlling factor in the ratio of the number of carbon stars to that of O-rich stars. The larger mass loss rate is helpful for preventing the carbon stars from forming. There may be a larger mass loss rate in the Galactic bulge than in the solar neighbourhood. Further work on this is desirable.

Acknowledgments

We are grateful to Dr Izzard for providing his Doctor's thesis. Lü Guo-Liang thanks Professor Zhanwen Han for helpful discussion and offering CPU time. We thank Dr Hoernisa Iminniyaz for correcting the English language in the manuscript.

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