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Effects of α-Enhancement on Stellar Evolution *

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Abstract Using Eggleton's code, we systematically show the differences in stellar evolution between the results based on the scaled-solar mixture and the α-enhanced metal mixture. As input, the OPAL high temperature opacities are used for $\log(T/\mathrm{K}) > 4.00$, and the new Wichita State low temperature opacities, for $\log(T/\mathrm{K}) \leq 4.00$. Our calculations cover star masses ranging from 0.25 to 80.0 $M_{\odot}$, spaced at $\Delta \log M = 0.10$ or 0.05. The values of metallicities Z are 0.0001, 0.0003, 0.001, 0.004, 0.01, 0.02, 0.03, 0.04, 0.06, 0.08 and 0.10. For a given Z, the initial hydrogen mass fraction is given by $X = 0.76 - 3.0Z$. We show that α-enhancement can raise the stellar effective temperature and luminosity, and reduce the evolutionary age. Compared with some previous work, the effects of α-enhancement are more obviously demonstrated in our calculations.

Key words: abundances — stars: evolution — stars: general

1 INTRODUCTION

Before the 1990s, solar metal mixture was adopted in the studies of the evolution of stars, clusters or galaxies. However, it is well known that solar metal mixture is not universal in the Galaxy or in extragalactic systems. From the 1990s on, many researchers have re-examined this issue (e.g., Bergbush & VandenBerg 1992; Salaris et al. 1993; Weiss et al. 1995; Salaris & Weiss 1998; Salasnich et al. 2000; Thomas & Maraston 2003; Ferguson et al. 2005; Pipino et al. 2007). Nowadays, it is widely accepted that [α/Fe] (see below) is capable of well describing the diversities of metal mixtures. In [α/Fe], α denotes any of the α-elements, including O, Ne, Mg, Si, S, Ar, Ca and Ti (Pietrinferni et al. 2006). Here Fe not only denotes the element Fe, but also all Fe-peak elements, including Cr, Mn, Fe, Co, Ni, Cu and Zn (Thomas, Maraston & Bender 2003). Generally, the values of [α/Fe] are calculated by number fractions of metal elements (e.g., Carney 1996; Cassisi et al. 2004). While if $[\alpha/\mathrm{Fe}] = 0.00$, the metal mixture is scaled-solar metal mixture. If $[\alpha/\mathrm{Fe}] > 0.00$, the metal mixture is α-enhanced metal mixture.

Observations of metal elements in some halo or bulge globular clusters of the Galaxy have shown that [α/Fe] is greater than zero, with a typical value $[\alpha/\mathrm{Fe}] \approx 0.3$ (e.g., Carney 1996; Carretta et al. 2001; Maraston et al. 2003). In addition, stellar populations in some elliptical galaxies, especially in some giant elliptical galaxies, also show $[\mathrm{Mg/Fe}] > 0$ (e.g., Worthey et al. 1992; Tantalo et al. 1998; Trager et al. 2000; Thomas & Maraston 2003; Pipino et al. 2007). As Mg is taken as representative of α-elements, $[\mathrm{Mg/Fe}] > 0$ reflects $[\alpha/\mathrm{Fe}] > 0$. Therefore, using one element, in particular iron, as the metal indicator, can be misleading when evaluating the metallicity of stars (Weiss et al. 2006), clusters or galaxies. For the α-elements are mainly produced by α-captures in type II supernovas and Fe-peak elements are mainly produced in type Ia supernovas, [α/Fe] reflects the effects of the two different modes of nucleosynthesis (e.g., Carney 1996; Thomas et al. 1999). Previously, one took that the individual element abundances within

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Table 1 Metal relative number fractions (# frac) and mass fractions (mass frac) in the GS98 scaled-solar mixture and the SW98 α-enhanced mixture.

Element	GS98 # Frac	GS98 Mass Frac	SW98 # Frac	SW98 Mass Frac
C	0.246023	0.172062	0.108345	0.076535
N	0.061798	0.050417	0.028507	0.023483
O	0.502315	0.468017	0.715919	0.673656
Ne	0.089326	0.104970	0.069963	0.083031
Na	0.001552	0.002078	0.000653	0.000883
Mg	0.028247	0.039988	0.029170	0.041697
Al	0.002296	0.003607	0.001001	0.001589
Si	0.026976	0.044126	0.021623	0.035717
P	0.000270	0.000487	0.000086	0.000157
S	0.011775	0.021991	0.010592	0.019972
Cl	0.000142	0.000292	0.000096	0.000201
Ar	0.001866	0.004342	0.001011	0.002375
K	0.000100	0.000228	0.000040	0.000093
Ca	0.001663	0.003882	0.002212	0.005215
Ti	0.000065	0.000181	0.000136	0.000384
Cr	0.000364	0.001102	0.000143	0.000437
Mn	0.000252	0.000805	0.000075	0.000242
Fe	0.023495	0.076413	0.009882	0.032459
Ni	0.001321	0.004517	0.000543	0.001874

the metal are of negligible influence, as long as hydrogen and helium dominate the gas. However, for opacities this no longer holds true since various elements contribute very differently to the total absorption (Weiss et al. 2006). Therefore, in most cases α-enhancement can raise the stellar effective temperature and luminosity, and reduce the evolutionary age.

Compared with previous works, there are some special features in our work. First, we systematically investigate the primary effects of α-enhancement on stellar evolution with more data of mass and metallicities, and explain these effects in more detail. Secondly, the studies before 2005 used the old Wichita state low temperature molecular opacity tables (Alexander & Ferguson 1994) (hereinafter AF94 tables), but AF94 tables for α-enhanced metal mixture are erroneous (Weiss et al. 2006). On the contrary, we use the new Wichita state low temperature molecular opacity tables (Ferguson et al. 2005) (hereinafter FA05 tables). Thirdly, Hurley's code of rapid stellar evolution (Hurley et al. 2000) is widely used in population synthesis with $Z \leq 0.03$. We can improve Hurley's code to study the effects of α-enhancement on population synthesis, and the metallicity can be as large as 0.10.

This paper is organized as follows. In Section 2, we describe how to construct the opacity tables. In Section 3 we show the physical inputs. In Section 4 we investigate the primary effects of α-enhancement on stellar evolution. We give a discussion and conclusions in Section 5.

2 CONSTRUCTION OF OPACITY TABLES

Opacity is a measure of the degree to which matter absorbs photons, and the changed opacity affects the stellar structure and evolution (Alongi et al. 1993; Stothers & Chin 1994; Chen & Tout 2007). We use OPAL high temperatures opacity tables (Iglesias & Rogers 1996; Eldridge & Tout 2004) (hereinafter OPAL96 tables) for the range $4.00 < \log(T/\mathrm{K}) \leq 8.70$, and the FA05 tables for $3.00 \leq \log(T/\mathrm{K}) \leq 4.00$. At $\log(T/\mathrm{K}) = 4.00$ the two tables match well.

In this paper, we adopt the scaled-solar metal mixture of Grevesse & Sauval (1998) (hereinafter GS98 scaled-solar mixture) and the α-enhanced metal mixture given by Salaris & Weiss (1998) (hereinafter SW98 α-enhanced mixture) with $[\alpha/\mathrm{Fe}] = 0.49$. See Table 1. For these two metal mixtures, the low temperature opacity tables, can be obtained from *http://webs.wichita.edu/physics/opacity/*.

The radiative opacities $\kappa_{\rm rad}$ (Rosseland mean opacity obtained from OPAL96 and FA05 tables) are supplemented with the conductive opacities $\kappa_{\rm con}$, according to the formulae of Yakovlev & Urpin (1980).

The opacity κ is obtained from

$$\frac{1}{\kappa} = \frac{1}{\kappa_{\rm rad}} + \frac{1}{\kappa_{\rm con}}. \tag{1}$$

At extremely high temperatures, the opacity is dominated by electron scattering, and relativistic effects are important. We fill this part with the formula of Iben (1975),

$$\kappa_{\rm e} = [0.2 - D - (D^2 + 0.004)^{\frac{1}{2}}](1 + X), \tag{2}$$

where $D = \log(T/10^6{\rm K}) - 1.7$, X denotes the hydrogen mass fraction. We use it at $8.70 < \log(T/{\rm K}) \leq 9.30$.

3 PHYSICS INPUTS

We use the stellar evolution code of Eggleton (1971, 1972, 1973), which has been updated with the latest input physics over the last three decades (Han et al. 1994; Pols et al. 1995; Pols et al. 1998). We set the convective overshooting parameter at $\delta_{\rm OV} = 0.12$ (Pols et al. 1997; Schröder et al. 1997). We also take Reimers' type mass-loss (Reimers 1975) into account, with Reimers's parameter $\eta = 1/4$. In our calculations, the stellar mass ranges from 0.25 to 80.0 $M_\odot$, totalling 30 values. Stars with masses from 0.25 to 0.80 $M_\odot$ and from 2.00 to 80.0 $M_\odot$ are spaced at intervals of $\Delta\log M = 0.10$. Stars with masses from 0.80 to 2.00 $M_\odot$ at intervals of $\Delta\log M = 0.05$. The reason that we use a narrower for the range 0.80–2.00 $M_\odot$ is as follows. First, the shape of the main sequence (MS) changes rapidly in this mass range (Pols et al. 1998). Secondly, stars in this mass range are generally located at the turn-offs of MS single stellar populations with ages greater than one giga year, and significantly affect the ages derived by evolutionary population synthesis (Zhang et al. 2002). The values of metallicities Z are 0.0001, 0.0003, 0.001, 0.004, 0.01, 0.02, 0.03, 0.04, 0.06, 0.08 and 0.10. For a given Z the initial hydrogen mass fraction is given by $X = 0.76 - 3.0Z$ (Pols et al. 1998).

4 EFFECTS OF α-ENHANCEMENT ON STELLAR EVOLUTION

For stars with masses lower than approximately 0.40 $M_\odot$, we follow their evolution from zero-age main sequence (ZAMS) to white dwarf. For stars with masses ranging from approximately 0.50 to 2.00 $M_\odot$, or larger than 16.0 $M_\odot$, we follow their evolution from ZAMS to the tip of the red giant branch. For stars with masses from around 2.00 to 16.0 $M_\odot$, we do the same from ZAMS to the tip of the asymptotic giant branch. As stated, in this paper we show the primary effects of α-enhancement on the stellar evolution. The data of stellar evolution are available at *http://www.ynao.ac.cn/~bps/download/jianpoguo/stellar-data.rar*. One may also send a request to *guojianpo1982@hotmail.com* for further information.

4.1 Effects of α-Enhancement for Stars with Different Metallicities

Generally the α elements and Fe-peak elements cover a large range of metallicity. As the metallicity increases, discrepancies in opacity between the scaled-solar mixture and the α-enhanced mixture become increasingly obvious; hence also the effects of α-enhancement on stellar evolution. We take two stars, one of $M = 1.00$ and one of 50.0 $M_\odot$ as illustrative example (see Fig. 1).

4.2 Effects of α-Enhancement for Stars with Different Masses

Influences of α-enhancement on evolutionary tracks for different mass can be seen from Figure 2. For stars with $M \leq 0.40\,M_\odot$, there are no obvious discrepancies between the scaled-solar mixture and the α-enhanced mixture. Since the central temperatures of these stars are not high, neither CN cycle nor CNO cycle will take place. Provided that the central temperature increases only by a little (in Subsection 4.3, we will explain why α-enhancement can make the central temperature higher), the efficiency of nuclear energy does not increase very much, and the effective temperature and the luminosity will not change greatly.

For stars with masses around 1.00 $M_\odot$, the effects of α-enhancement are most obvious when the effective temperature approaches maximum during the MS stage. We take a star of $M = 1.00\,M_\odot$ and $Z = 0.02$ as an example. When the star has evolved to the point of maximum effective temperature on the main sequence (the point marked A1 for the scaled-solar mixture, the point A2 for the α-enhanced mixture), the age is smaller by $\sim$17.8% for the α-enhanced mixture than for the scaled-solar mixture, the effective temperature is higher by $\sim$130 K, and the luminosity is higher by $\sim$13.2%.

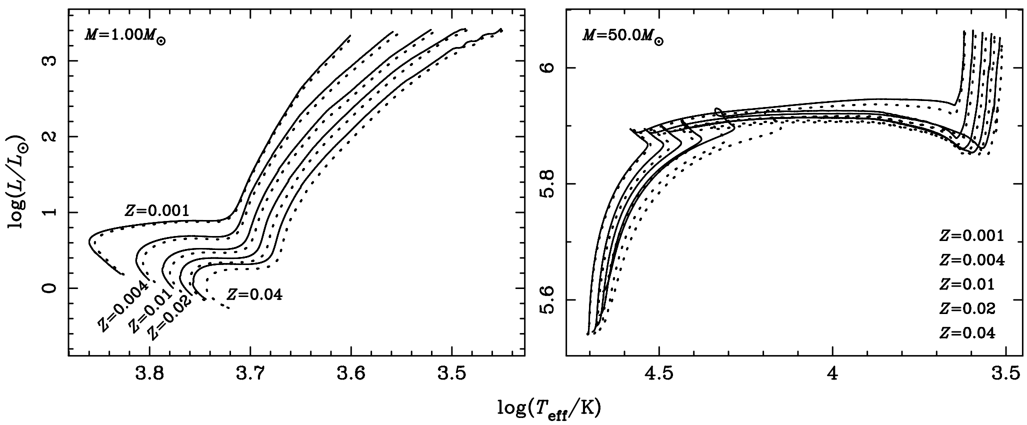

Fig. 1 Stellar evolutionary tracks of scaled-solar mixture (dotted lines) and α-enhanced mixture (solid lines), for $M = 1.00$ and 50.0 $M_\odot$, $Z = 0.001$, 0.004, 0.01, 0.02 and 0.04.

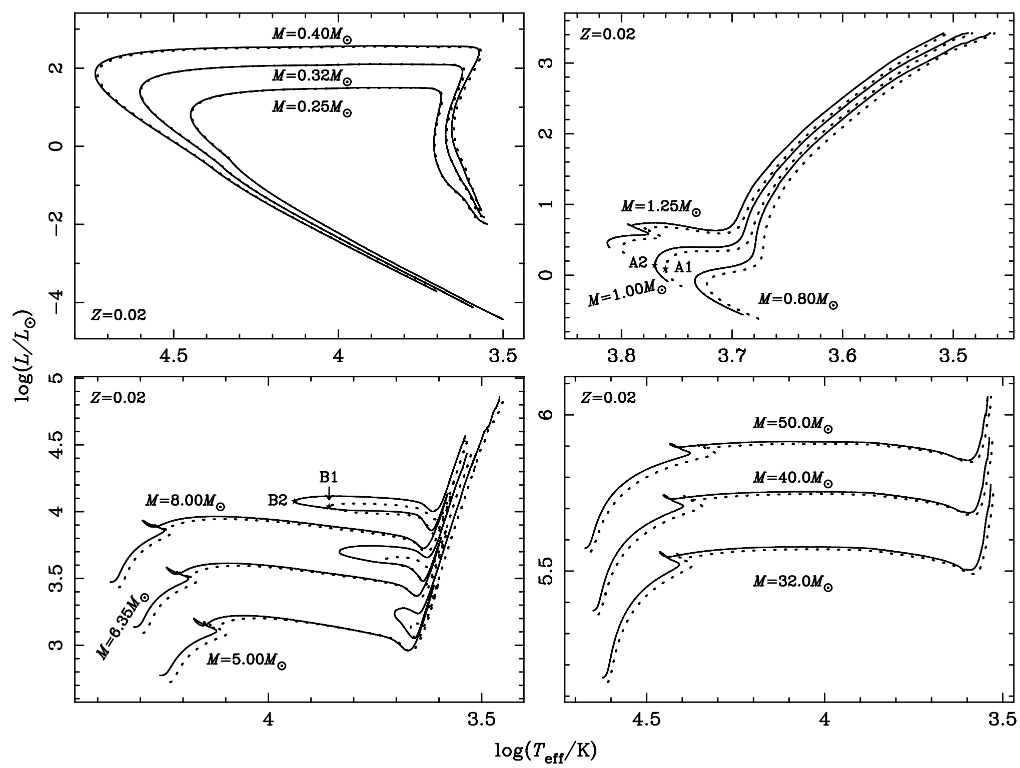

Fig. 2 Stellar evolutionary tracks of the scaled-solar mixture (dotted lines) and the α-enhanced mixture (solid lines), for $Z = 0.02$, $M = 0.25$, 0.32, 0.40, 0.80, 1.00, 1.25, 5.00, 6.35, 8.00, 32.0, 40.0 and 50.0 $M_\odot$.

For intermediate mass stars, α-enhancement can boost up the blue loop considerably. We take a star of $M = 8.00\,M_\odot$ and $Z = 0.02$ as an example. When it evolves to the point of maximum effective temperature in the blue loop phase (Point B1 for the scaled-solar mixture, B2 for the α-enhanced mixture), the age is smaller by $\sim$8.04%, the effective temperature is higher by $\sim$1472 K, and the luminosity is higher by $\sim$9.48% for the α-enhanced mixture than for the scaled-solar mixture.

For massive stars, the effects of α-enhancement are comparably significant in the main sequence.

4.3 Effects of α-Enhancement on Stellar Characteristics

As seen in Subsections 4.1 and 4.2, the α-enhanced model stars have higher luminosities and effective temperatures, and evolve more rapidly. We take a star of $M = 1.00\,M_\odot$ and $Z = 0.02$ as an example to illustrate the effects of α-enhancement on the stellar characteristics (see Fig. 3).

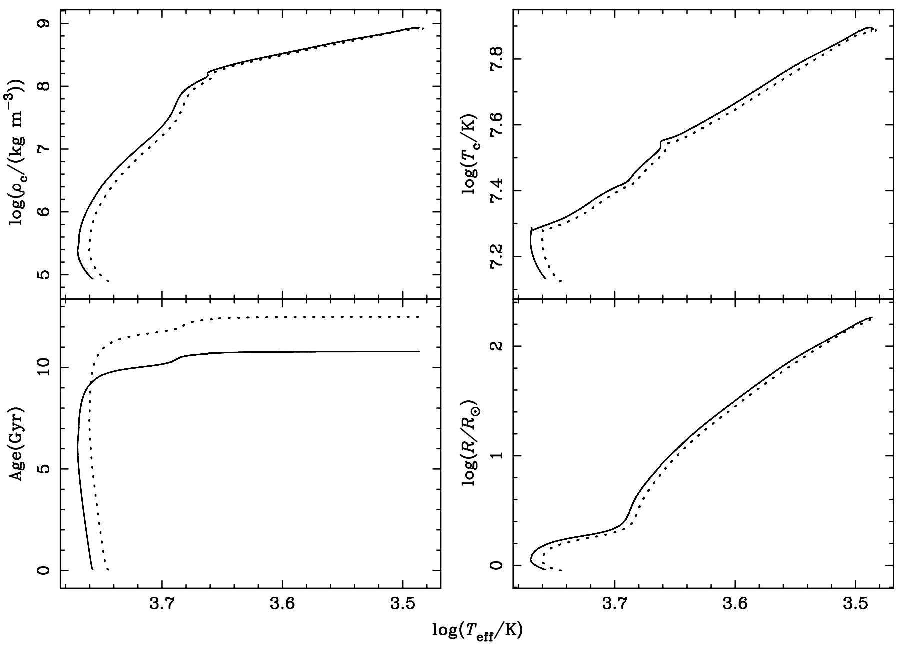

Fig. 3 Stellar evolutionary tracks with the scaled-solar mixture (dotted lines) and the α-enhanced mixture (solid lines), for $M = 1.00\,M_\odot$ and $Z = 0.02$. Plotted as functions of the effective temperature are the central density, ρ_c, central temperature, T_c , the radius, R and the age.

For a shell outside the nuclear burning zone, the total luminosity L_R satisfies the expression

$$\frac{L_R}{4\pi r^2} = -\frac{4acT^3}{3\rho\kappa_R}\frac{\partial T}{\partial r}, \tag{3}$$

where a is a constant, c is the velocity of light; r, T, ρ, κ_R and $\frac{\partial T}{\partial r}$ are respectively the radius, temperature, density, Rosseland mean radiative opacity and temperature gradient of the given shell. Generally the opacity is lower in the α-enhanced mixture than in the scaled-solar mixture, and a smaller κ_R leads to a lower $\frac{\partial T}{\partial r}$, hence, a higher surface temperature, along with a higher effective temperature $T_{\rm eff}$. Now, L_R satisfies the expression $L_R = 4\pi R^2\sigma T_{\rm eff}^4$, where R is radius of the star and σ the Stefan-Boltzmann constant. Provided that L_R is invariable, an increased $T_{\rm eff}$ leads to a decreased stellar radius. And the latter leads to an increased central density ρ_c and an increased central temperature T_c. A higher T_c raises the efficiency of nuclear energy, so L_R becomes larger. As a result, the star evolves more rapidly and the evolutionary age

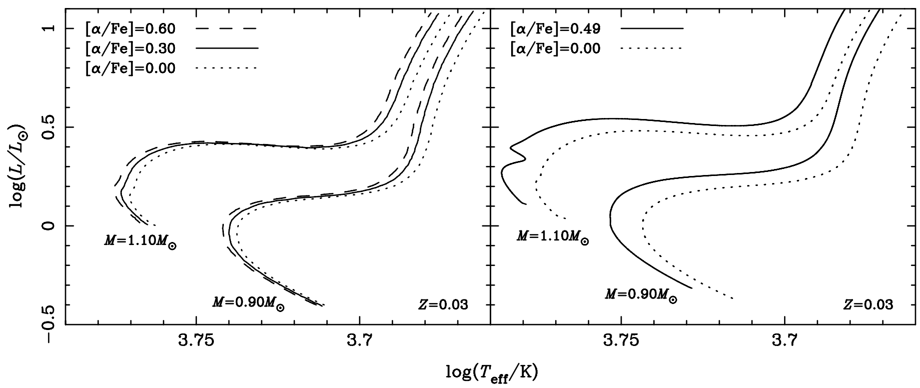

Fig. 4 Comparison between the stellar evolutionary tracks of VandenBerg et al. (left) and of ours (right), for $M = 0.90$ and $1.10\,M_{\odot}$, $Z = 0.03$. The left panel reproduces fig. 9 of VandenBerg et al. (2000).

becomes smaller. A higher $T_{\rm eff}$ gives rise to a decreased radius, but a larger $L_{\rm R}$ causes an increase in the radius. When taking all factors into account, the difference in radius between the scaled-solar mixture and the α-enhanced mixture is not obvious.

4.4 Comparison between VandenBerg et al. and This Paper

The studies by VandenBerg et al. (2000) on the subject of α-enhancement have been well regarded and widely used (e.g., Salasnich et al. 2000; Thomas & Maraston 2003; Pietrinferni et al. 2006; Weiss et al. 2006). Therefore, a comparison between their and our results should be useful. However, VandenBerg et al. (2000) and we used different stellar evolution programs, and some of the parameters used are also different. So, in order to show the effects of α-enhancement (not other factors) on stellar evolution, we compare the evolutionary tracks between us for two stars ($M = 0.90$ and $1.10\,M_{\odot}$, $Z = 0.03$). See the two panels of Figure 4. We find when the stellar luminosity reaches 1.1 solar luminosity, the relative mass losses in our calculations (for stars with $M = 0.90$ and $1.10\,M_{\odot}$, $Z = 0.03$) are all less than 0.3%, if we use $\eta = 1/4$, in other words, there is little influence of Reimers' type mass-loss on the stellar evolution in this phase. Also, the effect of overshooting at low masses is not visible (Pols et al. 1998). VandenBerg et al. (2000) did not state whether overshooting or mass-loss was taken into account. Accordingly, we did not include overshooting and Reimers' type mass-loss in our calculations for the comparison.

The discrepancies between the scaled-solar mixture and the α-enhanced mixture increase with increasing $[\alpha/\mathrm{Fe}]$. Therefore, as [α/Fe] increases, the effects of α-enhancement on stellar evolution become correspondingly more remarkable. Hence, the effects of α-enhancement with $[\alpha/\mathrm{Fe}] = 0.49$ should be more obvious than that with $[\alpha/\mathrm{Fe}] = 0.30$, but should be less obvious than that with $[\alpha/\mathrm{Fe}] = 0.60$, other things being equal. However, the effects of α-enhancement with $[\alpha/\mathrm{Fe}] = 0.49$ in our work are more obvious than that with $[\alpha/\mathrm{Fe}] = 0.60$ in VandenBerg et al. (2000). The reason for this might be as follows. First, VandenBerg et al. (2000) used the AF94 tables, which is erroneous for the α-enhanced mixture and should not be used any longer (Weiss et al. 2006). On the other hand, we used the FA05 tables. Secondly, VandenBerg et al. (2000) adopted the scaled-solar metal mixture presented by Grevesse et al. (1991). Whereas we adopted the GS98 scaled-solar metal mixture.

5 DISCUSSION AND CONCLUSIONS

Weiss et al. (2006) used the FA05 tables to study the effects of α-enhancement on stellar evolution. Their work mainly showed the different impacts on stellar evolution made by the FA05 tables and other low temperature opacity tables, and only for low-mass, high-metallicity stars. In our work, we use the FA05 tables for all stars, and systematically show the main effects of α-enhancement on stellar evolution for stars of different masses and different metallicities. We also quantitatively investigated the effects of α-enhancement on the blue loop, for intermediate-mass stars.

To sum up, α-enhancement can raise the effective temperature and luminosity of the star and shorten its evolutionary age. More figures and data of stellar evolution are available at *http://www.ynao.ac.cn/~bps/download/jianpoguo/stellar-data.rar*. One may also send any special request to *guojianpo1982@hotmail.com*. Since a stellar population is composed of a large numbers of stars, α-enhancement can also make the whole population brighter and bluer, and evolve more rapidly.

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