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Implementation of New OPAL Tables in Eggleton's Stellar Evolution Code *

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Abstract Based on previous works of OPAL, we construct a series of opacity tables for various metallicities $Z = 0$, 0.000 01, 0.000 03, 0.000 1, 0.000 3, 0.001, 0.004, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08 and 0.1. These tables can be easily used in Eggleton's stellar evolution code in place of the old tables without changing the code. The OPAL tables are used for $\log_{10}(T/\mathrm{K}) > 3.95$ and Alexander's for $\log_{10}(T/\mathrm{K}) < 3.95$. At $\log_{10}(T/\mathrm{K}) = 3.95$, the two groups' data fit well for all hydrogen mass fractions. Conductive opacities are included by reciprocal addition according to the formulae of Yakovlev and Urpin. A comparison of 1 and $5\,M\odot$ models constructed with the older OPAL tables of Iglesias and Rogers shows that the new opacities have most effect in the late stages of evolution, the extension of the blue loop during helium burning for intermediate-mass and massive stars.

Key words: radiative transfer — stars: evolution — stars: general

1 INTRODUCTION

In the 1970's Eggleton (1971, 1972, 1973) devised a stellar evolution code (PPE code in this paper), which has been updated with the latest physics over the last three decades (Han et al. 1994; Pols et al. 1995; Pols et al. 1998). The PPE code is now used worldwide because of its convenience, expediency and easy application to binary evolution. For example, this code and its stripped-down version EZ (rewritten by Bill Paxton in Fortran 90) are the main stellar evolutionary codes of MODEST (Modeling Denser Stellar system), which is a loosely knit collaboration between various groups working in stellar dynamics, stellar evolution and stellar hydrodynamics.

Opacity is a measure of the degree to which matter absorbs photons, and it significantly affects stellar evolution. Opacity tables are therefore important for a stellar evolution code. Four main processes influence the opacity in a star: the transition of an electron between two energy levels in an atom, ion or molecule (bound–bound), ionization of an atom or ion by an incoming photon with enough energy (bound–free), an electron and photon interacting near an atom or ion (free–free) and electron scattering. Composition, temperature and density all affect the opacity, and the calculation of opacities in a star is complicated and difficult. With the models of the above processes, the OPAL group presented their original opacity tables in 1992 (Iglesias & Rogers 1992) (hereinafter OPAL92). Since then they have further considered the details of their models (Iglesias & Rogers 1996, IR96) and presented new opacity tables [1] (hereinafter

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[1] available at http://www-phys.llnl.gov/Research/OPAL

OPAL96). In comparison with OPAL92, OPAL96 has made improvements in the physics and numerical procedures as well as some corrections to their code. Here we give a brief description of the improvement in the physics; for more details see the paper IR96. The main feature of OPAL96 is the inclusion of seven more metals in addition to the original 12 metals. Full intermediate coupling is used for Ar and heavier elements while LS coupling is used for the lighter elements. The absorption and scattering from various H and He species are included (only the formation of H_2 is considered in OPAL92). Also the red wings of line profiles are included and the effect of neutral H and He on spectral line broadening is considered. For ionization balance, the Debye-Hückle approximation is used in OPAL92 while higher order Coulomb terms are included in OPAL96. All these modifications affect the opacities. The inclusion of 19 metals leads to an increase in opacity by as much as 20 percent for population I with solar metallicity $Z = 0.02$. The changes in opacity induced by other modifications are less than 10 percent.

The opacity changes will affect the stellar structure and evolution, especially for intermediate-mass and massive stars, as has been discussed by several previous papers (Alongi et al. 1993; Stothers & Chin 1994). The models with OPAL96 will also exhibit some differences in structure and evolution compared to those with OPAL92. These differences are probably not very large (see Sect.3 in this paper). However, OPAL96 has become the most comprehensive opacities available today. In IAUS 241, which will be held from 10–16 December 2006 in Spain, there are two so-called challenges, and one is in stellar evolution. In this challenge, OPAL96 and the data from Alexander & Ferguson (1994) are appointed as the opacity inputs in the physical specifications. Meanwhile, as a stellar evolutionary code, it is necessary to improve it with new physics and new physical inputs, and researchers are always willing to apply these in order to improve the accuracy of evolutionary calculations.

Eldridge & Tout (2004) took a detailed look at, and implemented the opacity for enriched carbon and oxygen mixtures with OPAL96. They also provided a new stellar code with a new routine to read their opacity tables. In particular they use the variable $R = \rho/T_6^3$, where ρ is the density, $T_6 = T/10^6\,\mathrm{K}$ and T the temperature. Then $\log_{10}(T/\mathrm{K})$ ranges from 3.0 to 10 and $\log_{10}(R/\mathrm{g\,cm^{-3}})$ from -8.0 to 7.0. At low temperatures ($\log_{10}(T/\mathrm{K}) < 4.0$), they use the data of Alexander & Ferguson (1994) and for high temperatures ($8.7 < \log_{10}(T/\mathrm{K}) < 10$) they fill the table using the fits of Iben (1975). The major conclusion of their study is that the changes induced by properly including opacities for varying C and O mixtures are small, but may improve the numerical stability in the late stages of evolution, because they resolve changes with composition in greater detail. Their code and tables are available at *http://www.ast.cam.ac.uk/stars*.

At present, many astronomers are still using the old version of the code and the most widely used opacity tables in it were constructed by Pols et al. (1995) from OPAL92. The metallicities, Z, considered by these tables are 0.0001, 0.0003, 0.001, 0.004, 0.01, 0.02 and 0.03. These Z values may fulfil the needs of most studies. However, for some special objects, e.g., the objects of Population III or those in the center of the Milky Way (with about 3 times solar metallicity), it is necessary to enlarge the range of Z values. Therefore we have constructed a series of opacity tables in the form of Pols et al. (1995), in the ($\log\rho$, $\log T$) space of OPAL96 calculated for Z values 0, 0.000 01, 0.000 03, 0.000 1, 0.000 3, 0.001, 0.004, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08 and 0.1. These tables can be implemented in the PPE code just as the old opacity tables, and have no influences on stellar evolution in comparison to those from more detailed C and O mixtures except for numerical stability in the late stages as shown in Eldridge & Tout (2004). We present zero-age main-sequence models of various metallicities, Z, and some evolved models for examination and comparison to models made with other tables.

2 TABLE CONSTRUCTION

In OPAL96, $\log_{10}(T/\mathrm{K})$ ranges from 3.75 to 8.70 and $\log_{10}(R/\mathrm{g\,cm^{-3}})$ from -8 to 1. Alexander & Ferguson (1994) derived molecular and grain opacities for low temperatures ($\log_{10}(T/\mathrm{K})$ from 3.0 to 4.1). We use OPAL tables for $\log_{10}(T/\mathrm{K}) > 3.95$ and Alexander's for $\log_{10}(T/\mathrm{K}) < 3.95$. At $\log_{10}(T/\mathrm{K}) = 3.95$, the two sets of data match well. The radiative opacities, κ_{rad} (Rosseland mean opacity obtained from OPAL and Alexander tables), are supplemented with conductive opacities, κ_{con}, according to the formulae of Yakovlev & Urpin (1980). The opacity κ is obtained from

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

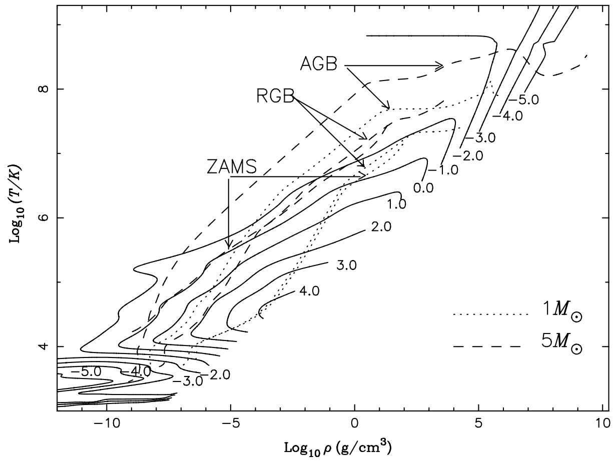

Fig. 1 Contours of $\log\,\kappa$ in ($\log T$, $\log \rho$) space at $\log_{10}(\kappa/\mathrm{cm}^2\,\mathrm{g}^{-1}) =$ 4.0, 3.0, 2.0, 1.0, 0.0, -1.0, -2.0, -3.0, -4.0 and -5.0. The dotted lines show the internal structure of a $1M_\odot$ star in this space at different evolutionary stages: zero-age main sequence (ZAMS), red giant branch (RGB) and asymptotic giant branch (AGB). The dashed lines are similar models of a $5M_\odot$ star.

We construct a rectangular table in $\log \rho$, $\log T$ space with $-12 < \log_{10}(\rho/\mathrm{g\,cm^{-3}}) < 10$ in steps of 0.25 and $3 < \log_{10}(T/\mathrm{K}) < 9.3$ in steps of 0.05. At very high temperatures ($\log_{10}(T/\mathrm{K}) > 8.7$), the opacity is dominated by electron scattering, and relativistic effects are important. We fill this part with the formula of Iben (1975),

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

where $D = \log_{10} T_6 - 1.7$.

Outside the ranges of R, values are obtained by extrapolation in the old opacity tables. These parts have no real validity for stellar evolution, so we simply fill them with boundary values. The Z values specifically calculated are 0, 0.000 01, 0.000 03, 0.000 1, 0.000 3, 0.001, 0.004, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08 and 0.1. For each Z, $(X, X_\mathrm{C} + X_\mathrm{O}) = (0.8, 0.0)$, (0.7, 0.0), (0.5, 0.0), (0.35. 0.0), (0.2, 0.0), (0.1, 0.0), (0.0, 0.0), (0.0, 0.5), (0.0, 0.8) and (0.0, $1 - Z$), where X is the hydrogen mass fraction and $X_\mathrm{C} + X_\mathrm{O}$ the sum of enhanced carbon and oxygen following helium burning.

3 RESULTS AND COMPARISONS

For $Z = 0.02$ contours of $\log \kappa$ in ($\log T$, $\log \rho$) space are presented in Figure 1. The structures of stars of $1M_\odot$ and $5M_\odot$ at different evolutionary stages: zero-age main sequence (ZAMS), red giant branch (RGB) and asymptotic giant branch (AGB), are also shown in this figure. We see that the two stars stay in the ranges given by the OPAL and Alexander tables throughout their lives. For more massive stars, the density decreases and the temperature increases, so that the three lines move up to the left, far away from the boundary.

Figure 2 presents the evolutionary tracks for stars of $1\,M_\odot$ and different Z. The circles in the tracks are at the point when $X \approx 0.001$ in the centre of the star. The lifetime t_MS, $\log_{10}(R/R_\odot)$, $\log_{10}(L/L_\odot)$ and $\log_{10}(T_\mathrm{eff}/\mathrm{K})$ at the circles are listed in Table 1. We can see core contraction when the central hydrogen is nearly exhausted for stars with $Z > 0.05$. This indicates that a convective region develops in the centre of these stars. In fact a central convective region already exists at the end of main-sequence evolution in a star with $Z = 0.04$ (see Fig. 3).

Combining Table 1 and Figure 2 we see that t_MS decreases with luminosity as Z ranges from 0.000 01 to 0.000 3. This differs from the usual expectations in stellar evolution – larger luminosity results in a shorter lifetime on the main sequence. This discrepancy is driven by the variation of opacity with Z which increases the size of the burning core even though there is little difference in the central hydrogen mass fraction over this range of Z.

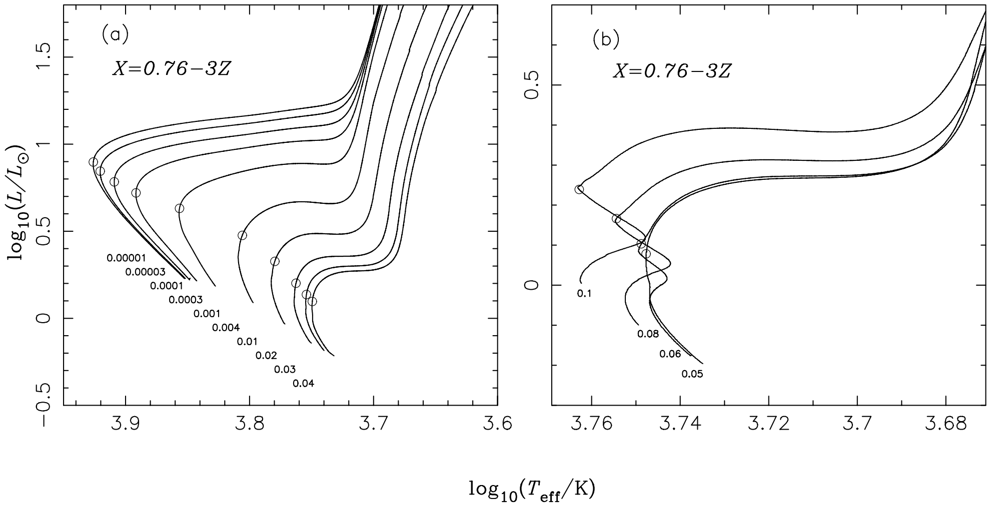

Fig. 2 Evolutionary tracks for a star of $1\,M_\odot$ with different metallicities ($Z = 0.000\,01$, $0.000\,03$, $0.000\,1$, $0.000\,3$, 0.001, 0.004, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08 and 0.1). The initial hydrogen mass fraction X is $0.76 - 3Z$ in each case.

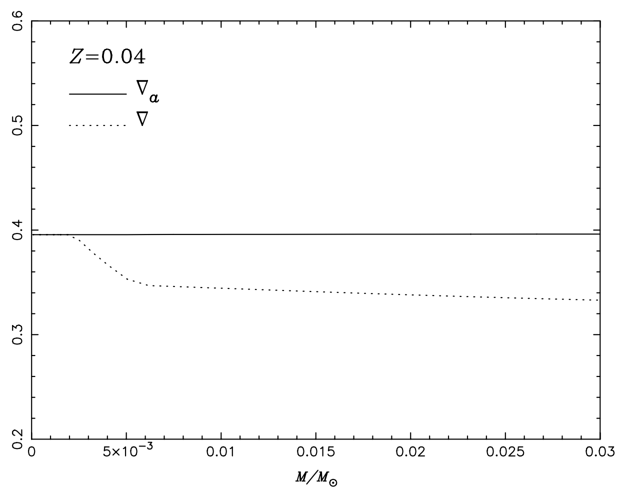

Fig. 3 Profiles of adiabatic temperature gradient $\nabla_{\rm ad}$ and actual temperature gradient ∇ in a star of $1M_\odot$ with $Z = 0.04$.

Table 1 Some parameters for the stars in Figure 2 when the central hydrogen mass fraction is about 0.001. The main-sequence lifetime $t_{\rm MS}$ is the time from zero-age main sequence to this point which is marked by a circle on each track.

Z	10^{-5}	3×10^{-5}	10^{-4}	3×10^{-4}	10^{-3}	4×10^{-3}	0.01	0.02	0.03	0.04	0.05	0.06	0.08	0.1
$t_{\rm MS}/10^9$ yr	5.544	5.432	5.324	5.229	5.310	6.876	7.560	9.085	9.576	9.297	8.550	7.922	6.343	4.500
$\log_{10}R/R_\odot$	0.120	0.105	0.097	0.100	0.126	0.150	0.128	0.099	0.083	0.073	0.067	0.078	0.098	0.117
$\log_{10}L/L_\odot$	0.897	0.845	0.783	0.720	0.631	0.476	0.327	0.201	0.136	0.096	0.078	0.104	0.166	0.239
$\log_{10}T_{\rm eff}/{\rm K}$	3.926	3.920	3.909	3.892	3.856	3.806	3.780	3.763	3.754	3.749	3.748	3.749	3.754	3.763

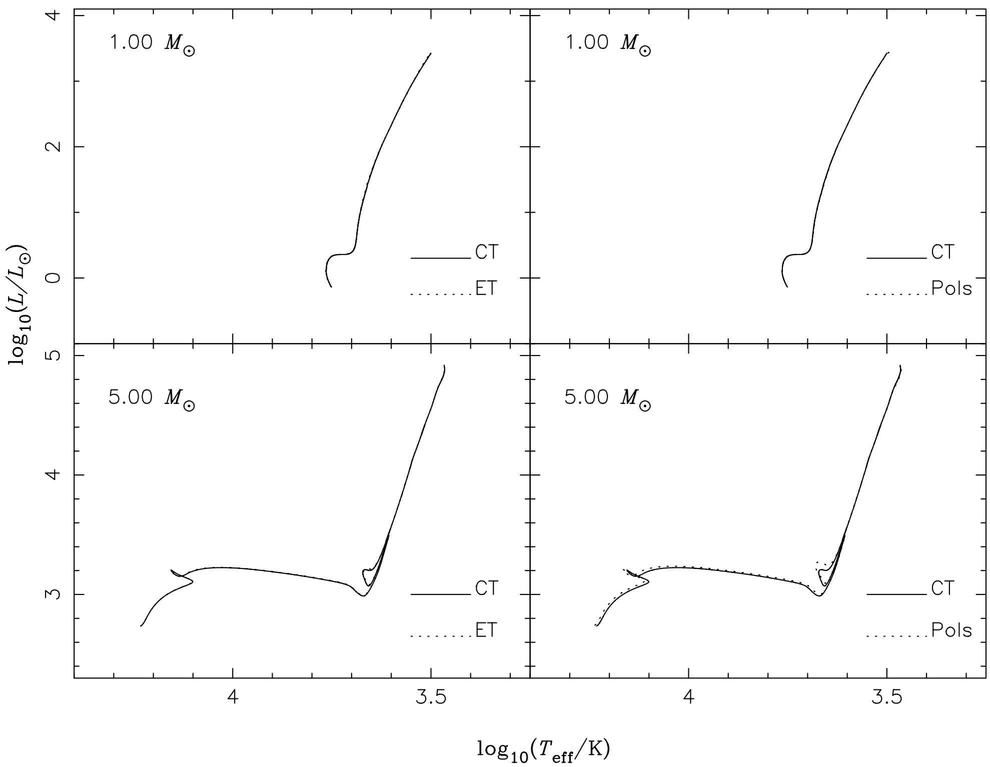

Fig. 4 Evolutionary tracks of stars of $1M_\odot$ and $5M_\odot$ for different opacities for $Z = 0.02$. The opacities are from Pols et al. (1995), Eldridge & Tout (2004) and this work (CT). For $1M_\odot$ the three are exactly overlapped, while for $5M_\odot$ the lines from ET and CT are also well matched.

For comparison, we show the evolutionary tracks of a star with $1M_\odot$ and $5M_\odot$ for different opacities when $Z = 0.02$ in Figure 4. The solid lines give the results of this work (CT in the figure) and the dotted lines that of Pols et al. (1995) (Pols) and Eldridge & Tout (2004) (ET). We see that the three tracks for $1M_\odot$ precisely overlap. For $5M_\odot$, the tracks of CT and ET are also well-matched while those of CT and Pols have some discrepancies on the main sequence and blue loop. The divergences of CT and Pols are due to the 20 percent increase in opacity of OPAL96 in comparison with OPAL92. As discussed by Stothers & Chin (1994), the development and extension of blue loop are strongly dependent on opacity. Since the main opacity changes are due to the inclusion of more metal elements and the treatments on them, the discrepancies of the results between OPAL92 and OPAL96 for intermediate-mass and massive stars may be larger with increasing Z. Therefore, we can expect the new opacity tables to improve the accuracy of stellar models of intermediate-mass and massive stars.

The opacity changes may also affect stellar structures. The increase of opacity means an enhancement of energy fraction absorbed as the energy passes through a certain matter. Therefore, a star with higher opacities (i.e., from OPAL96) has a lower luminosity and a larger radius as well as a smaller surface effective temperature. Another relatively important feature with opacity increase is the size of the central convective region for intermediate-mass and massive stars. The radiation temperature gradient $\nabla_{\rm rad}$ is proportional to opacity for certain conditions. Furthermore, the opacity increase will cause an increase of $\nabla_{\rm rad}$, as the convective criteria (whether for the Ledoux criterion or Schwarzschild criterion) are fulfilled more easily. The enlargement of the central convective region will contribute to energy production, and thus to the surface luminosity of a star. A new equilibrium will be first built in the star with new opacities and the surface luminosity of the star will be even lower than that with lower opacities (Fig. 4) in the equilibrium. The core mass and stellar radius for the $5M_\odot$ model with OPAL92 and OPAL96 are illustrated in Figure 5. The models with OPAL96 (i.e., ET and CT) have slightly longer times on the main sequence. The age differences

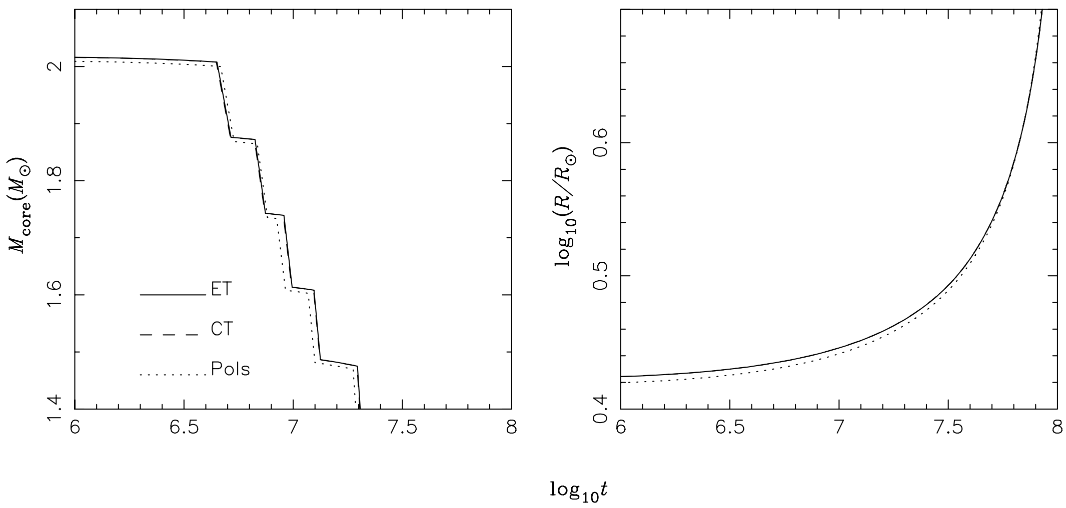

Fig. 5 Core mass and stellar radius as functions of age for the $5M_\odot$ model for different OPAL tables. The lines from ET and CT are precisely overlapped.

are about 5×10^7 yr and 3×10^6 yr for $1M_\odot$ and $5M_\odot$, respectively. Alongi et al. (1993) presented the influences of various opacity calculations on the stellar core mass and on the surface luminosity. Though the differences between OPAL92 and OPAL96 are not so obvious as those between LAOL and OPAL92 as compared by Alongi et al. (1993), our discussion here is similar to those results.

Our tables and ZAMS models (0.1< $M/M_\odot$ <160 for various metallicities) are available at *http://www.ynao.ac.cn/ bps*. One may also send a request to *xuefeichen717@hotmail.com* for them.

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