A&A 453, 769–771 (2006)
DOI: 10.1051/0004-6361:20054701

Astronomy & Astrophysics

New grids of stellar models including tidal-evolution constants up to carbon burning

III. From 0.8 to 125 $M_{\odot}$: the Large Magellanic Cloud (Z = 0.007–0.01)*

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Received 16 December 2005 / Accepted 7 March 2006

ABSTRACT

In this paper, we present new specific stellar models for the Large Magellanic Cloud. In order to take the observational uncertainties in the chemical composition into account, we have computed two grids: (X, Z) = (0.730, 0.010) and (0.739, 0.007). The covered mass range was 0.80 up to 125 $M_{\odot}$. The effects of rotation can be investigated by using the gravity-darkening exponents that are available for each track. The tidal constant E_2, depth of the convective outer zone, and the radius of gyration are computed and presented in a suitable format for studying the tidal evolution of a given close binary. The isochrones (and also those corresponding to the previous grids) will be presented in a future paper.

Key words. stars: evolution

1. Introduction

The double-lined eclipsing binaries (DLEB) are invoked as one of the most reliable tools for obtaining stellar masses, radii, and effective temperatures. Nowadays with the advance in observational techniques, the investigation of DLEB is possible even in other galaxies allowing the theoretical predictions of stellar models to be tested in different chemical environments, in particular in the Large Magellanic Cloud (LMC). Due to their intrinsical characteristics, DLEB seem to be ideal distance indicators for the LMC. However, that is not a simple task. The distance modulus of the LMC has been the theme of many controversies for a long time (for a recent review see Walker 2003). Alves (2004) reviews the status of the distance modulus of LMC on the basis of red clump giants, intrinsic variable stars (cepheid, RR Lyr, and Mira), cluster colour-magnitude fitting, supernova event (1987A), the tip of red giants, and eclipsing binaries. Although he found a convergence toward a single value, he also indicates that the eclipsing binaries presented a large internal scatter when compared with the average measurement error.

Some of these DLEB are, however, interacting systems, and their astrophysical properties are not as accurately determined as those for noninteracting ones (Fitzpatrick et al. 2003); this may be a partial explanation of the internal scatter. In our opinion, other factors may also be present such as the difficulty of determining the effective temperatures with confidence. While the radii and masses are determined from light and radial velocities curves with a good accuracy, the same does not always occur with the effective temperatures, which are dependent on semi-empirical calibrations, on model of atmospheres, on the adopted extinction law, etc. These limitations severely restrict the error bars for $T_{\rm eff}$ in DLEB. In other words: the estimation of error bars is, in some cases, rather optimistic.

An alternative way to test the stellar models, when the effective temperature determination in DLEB is not accurate enough, is to use the effective temperature ratio (TR), which is determined well from the light curves analysis and is free of previous calibrations (for the cases of V380 Cyg and EK Cep see Claret 2003, 2006). At the first glance, it seems that this procedure is a step back since it does not use the complete set of information (absolute values of the effective temperature). However, it is surely a more realistic step in these cases where no reliable values of effective temperatures are available.

Computating the present specific stellar models for the LMC provides a theoretical tool for exploring the capability of DLEB as a true astrophysical laboratory and disentangling all the problems. The applicability of the models is not only restricted to absolute dimensions. As mentioned in Claret (2005a, Paper II), about 4700 eclipsing binaries located at LMC are being used by Faccioli et al. (2005) to test their levels of circularization. In order to provide theoretical support to this kind of comparison, the parameters used to follow the tidal evolution of close binaries such as the depth of the convective envelope $x_{\rm bf}$, the radius of gyration β, as well as the tidal torque constant E_2 for stars with higher effective temperatures, are also made available.

2. Applicability of the models

The present calculations are a continuation of the previous grids (Claret 2004, hereafter Paper I, Claret 2005a) and are suitable for the Large Magellanic Cloud. They were computed for two metallicities (Z = 0.007–0.010), given the estimation of the observational uncertainties in the metal content (Ribas 2004).

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* Tables 1–60 are only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/453/769`
Additional data are available on CD ROMs upon request.

Table 1. Summary of the input physics of the models.

Mass range	0.8–125 $M_\odot$
Chemical composition	(X = 0.730, Z = 0.010), (X = 0.739, Z = 0.007)
Mixing-length parameter α	1.68
Core overshooting $\alpha_{\rm ov}$	0.20
Opacities (high temperatures)	Iglesias & Rogers (1996)
Opacities (low temperatures)	Alexander & Fergunson (1994)
Neutrinos	Itoh et al. (1989)

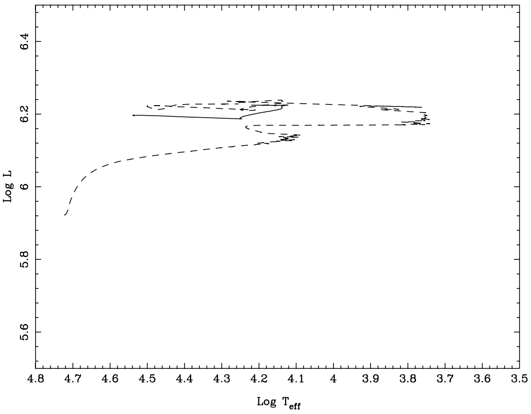

Fig. 1. Influence of the new mass loss rate in the evolution of a 80 $M_\odot$ model. See text.

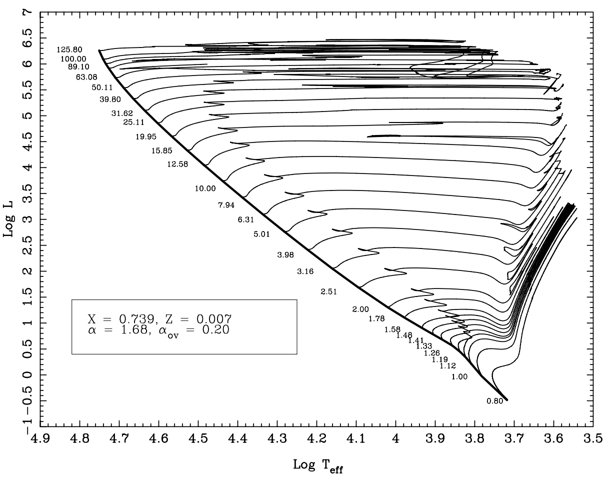

Fig. 2. The theoretical HR diagram for Z = 0.007. The numbers below the tracks indicate the stellar masses in solar units.

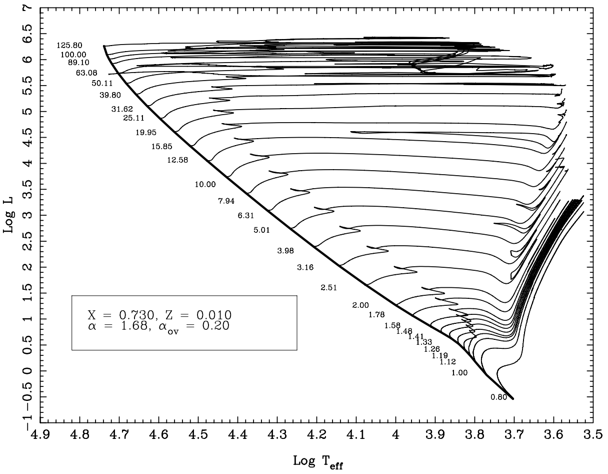

Fig. 3. The theoretical HR diagram for Z = 0.010. Same remarks as in Fig. 2.

The basic input physics of the evolution code such as opacities, equation of state, nucleosynthesis, convection theory, core overshooting, etc., were discussed in Papers I and II so will be not repeated here; they are summarised in Table 1.

However, the models presented in those papers were computed during the Wolf-Rayet phases using the parametrisation by Langer (1989) – WNE and WC – while for the WNL stars, the formalism by Conti (1988) was adopted. In such parametrisations, there is no dependence on the metallicity. More recent determinations of the mass loss rate for Wolf-Rayet stars indeed indicate a dependence not only on metallicity but also on the luminosity (Nugis & Lamers 2000). Figure 1 shows a series of models with 80 $M_\odot$ computed with the new mass loss rate (continuous line) and the old ones (dashed line). The differences, as expected, are larger as the models reach the Wolf-Rayet phase. Of course, the difference will depend on the mass of the model and on the adopted metallicity. The present models were computed by adopting the formalism by Nugis & Lamers (2000). To improve the nuclear network, we adopted the recent measurement of the rate for the reaction ^{14}N(p,γ)^{15}O (Runkle 2003; Formicola et al. 2004).

A general view of the models can be seen in Figs. 2 and 3 where the HR diagrams for (X, Z) = (0.739, 0.007) and (0.730, 0.010) are shown. For the sake of clarity, the tracks of more massive models are displayed only for the main-sequence. The effects of changing the chemical composition can be seen in Fig. 3 for some selected models. As expected, the models with lower metallicity are hotter: the differences in effective temperature are of the order of the present observational accuracy and could distinguish between both sets of models.

2.1. Tidal interactions

Some years ago, Claret (1999) investigated the apsidal-motion of HV 2274, an eclipsing binary located at the LMC with masses 12.1 ± 0.1 and 11.4 ± 0.4 $M_\odot$. This was the first case of an extragalactic binary system that was studied concerning the absolute dimensions and tidal interactions simultaneously. The theoretical radii and apsidal motion rate inferred from models computed for the precise observed masses were found to be in good agreement with observational data. On the other hand, Michalska & Pigulski (2005) found fourteen systems showing clear evidence of apsidal-motion. This makes the present calculation of the harmonics k_2, k_3, and k_4 very useful for testing the mass distribution of the stars showing apsidal-motion.

The tidal evolution of close binary stars located at LMC can also be investigated, since the main parameters used to compute the synchonization and circularization times, say, the depth of the convective envelope, the tidal constant E_2, etc., are provided

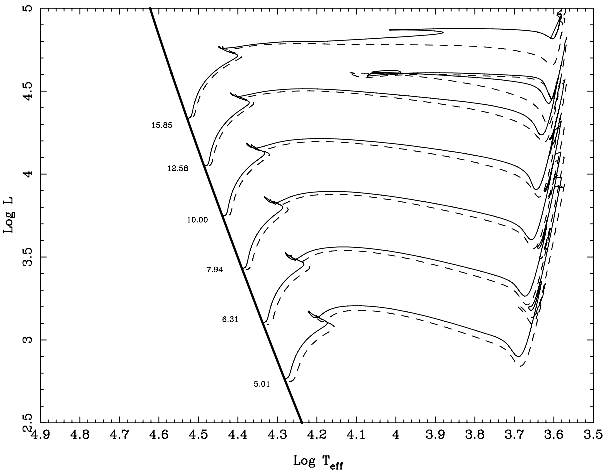

Fig. 4. The effect of the metallicity on the morphology of the tracks. Continuous lines represent models with $(X, Z) = (0.739, 0.007)$ and dashed ones denote models with $(X, Z) = (0.730, 0.010)$.

for each model. Note that there are still serious problems with the tidal evolution of close binaries concerning the comparison between theory and observations, so the present models may be useful (for more details, see Meibom & Mathieu 2005; and Claret 2005b).

2.2. *Massive binaries*

Another application for the present models, in addition to the standard applications to the stellar evolutionary models, is to compare the astrophysical properties of very massive stars belonging to eclipsing binaries systems. In fact, Ostrov & Lapasset (2002) and Ostrov (2003) report eclipsing binaries with masses of the order of 100 $M_{\odot}$. This is an excellent opportunity to test the capability of the theoretical models since there is no representative compilation of massive stars with masses higher than approximately 30 $M_{\odot}$.

2.3. *Chemically peculiar stars and clusters*

The grids of models can also be used to study chemically peculiar stars (CPS) in the LMC by using the Δa photometric system (Maitzen 1976). Such a system gives the broad band absorption features around 5200 Å, which is related to the non-solar abundance and to the presence of strong magnetic fields in CPS (Kupka et al. 2004). Appropriate theoretical isochrones were computed for the Δa photometric system and were extended to the present grids (Claret et al. 2003). Recently the present calculations were used prior to publication to check the reddening and distance modulus for two fields of the LMC (see Paunzen et al. 2005). The isochrones of the present grids (and also those corresponding to the grids published in Papers I and II) will be the subject of a separate paper. In addition to the usual isochrones format – Johnson and Strömgren color index, $M_{\rm v}$, $M_{\rm bol}$, etc. – we will provide the Δa photometric index.

2.4. *Rotation and tides*

The level of accuracy in some measurements of the stellar distortion is really high. By using the microlens event MOA 2002-BLG-33, Rattenbury et al. (2005) were able to obtain the oblateness of a distant – 5000 pc – dwarf star. The resulting angular resolution is around 0.04 μarcsec. In addition to the reliable limb-darkening calculations, such accuracy demands precise calculations of how the flux is distributed over the surface of rotating or tidally distorted stars. In order to provide the elements for computing the flux distribution over a stellar surface, we provide the gravity-darkening exponent β_1 for each point of these evolutionary tracks following the method developed by Claret (1998, 2000). In this way, the brightness distribution can be calculated for isolated rotating stars and /or for distorted components – by rotation and tides – of close eclipsing binaries.

In the near future, we will give β_1 for the isochrones, too. In this way, it will possible to investigate the effects of rotation when compared with standard isochrones for several angular velocities and inclination angles (Claret & Pérez Hernández 2006).

3. Tables

The models (60 tables) can be retrieved from the CDS via ftp anonymous, but here we briefly describe the tables: the first five columns of the tables contain the age (in years), log L (in solar units), log g, log $T_{\rm eff}$, and the mass (in solar units). Columns 6–9 contain the logarithm of the mass-loss rate ($M_{\odot}$/year), the logarithm of the central temperature, the logarithm of the density, and the core $q_{\rm c}$ in fraction of the total mass of the star. Columns 10–35 contain the central and surface chemical composition of X, Y, ^{12}C, ^{13}C, ^{14}N, ^{16}O, ^{17}O, ^{18}O, ^{20}Ne, ^{22}Ne, ^{24}Mg, ^{25}Mg, and ^{26}Mg. In the next three columns we have log k_2, log k_3, and log k_4. The depth of the convective envelope $x_{\rm bf}$ is given in Col. 39, while log E_2 is given in Col. 40. The constant E, the form factor $\alpha_{\rm P}$, and β are given in positions 41, 42, and 43, and Col. 44 gives the gravity-darkening exponent β_1 (for more details, see Paper I).

Acknowledgements. I am grateful to L. F. Miranda, who helped to improve the paper. The Spanish MEC (AYA2003-04651) is gratefully acknowledged for its support during the development of this work.

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