ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

Astron. Astrophys. Suppl. Ser. **133**, 123–127 (1998)

Stellar models for a wide range of initial chemical compositions until helium burning*

IV. From $X = 0.65$ to $X = 0.80$, for $Z = 0.004$

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Received March 9; accepted May 15, 1998

Abstract. As a continuation of previous papers in a series devoted to the computation of stellar structure and evolution models we present a grid specifically obtained for detailed studies of the stellar content of the Small Magellanic Cloud. The initial metal content has thus been adopted to be $Z = 0.004$ while the hydrogen content varies from 0.65 to 0.80 leaving as an intermediate value that given by standard laws of enrichment, $X = 0.744$. Interpolation for different environment is therefore possible with these new models. Other input physics parameters, e.g. convective overshooting, mixing-length, opacities or nuclear reaction rates, have been adopted to be homogeneous with the previously published models in order to facilitate comparative studies.

Key words: binaries: eclipsing — stars: evolution; interiors; fundamental parameters — Magellanic Clouds

1. Introduction

Studies on stellar structure and evolution are obviously very important for the understanding of the nature of galaxies. Population synthesis methods have shown that the availability of a wide range of reliable stellar models is needed for this purpose. The situation concerning galaxies of the Local Group being particularly interesting because individual stars can be studied and compared directly with evolutionary models. Stellar astronomy research can thus be developed in these objects very much in a similar way as we do in our own galaxy.

The purpose of studying individual stars in galaxies of the Local Group, mainly in the Magellanic Clouds is twofold. First, information about the constituents will allow a better understanding of the galaxies themselves, their structure and nature. Secondly, for those interested in stellar structure and evolution, the study of members of other galaxies will allow the test of available models and input physics in non-standard conditions from the point of view of initial chemical composition or formation environment.

2. Binary stars in the Magellanic Clouds

Because of their proximity, the Magellanic Clouds have been the main target of these studies in the past and many research papers or reviews have been devoted to them. But the situation will improve dramatically with the study of double-lined eclipsing binaries within them. In fact, it is well known that binary stars for which accurate absolute dimensions can be derived are the best source of fundamental information for studies on stellar structure. Double-lined eclipsing systems are the best way to obtain stellar masses and radii without any need for astrophysical calibrations.

It is also well-known that currently available theoretical models reproduce quite satisfactorily the stellar component of our galaxy providing additional information on chemical compositions and ages. But there are still some uncertainties in the models concerning the treatment of convection, rotation, and distribution of the chemical composition. The possibility to test the models in different conditions is expected to be very fruitful in this concern if accurate enough data are used.

In the past, the monitoring of eclipsing binaries in the Magellanic Clouds was not an easy task. Gaposhkin (1970, 1977) provided lists of candidates with periods and low

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* Tables 1-72 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/Abstract.html

quality light curves derived from photographic plate surveys aimed to the detection of new pulsating stars and the determination of the distance scale. Though this sample was used by Dworak (1974) to estimate also the distance to the Clouds using the photometric elements and an average mass-luminosity relation, the results were, as could be expected, not accurate enough (de Vaucouleurs 1978). The obtention of better light curves was attempted by several authors (Herczeg 1982) using photoelectric photometry, but it was not until the work by Jensen et al. (1988) when it was clearly shown that CCD light curves could be obtained with an accuracy (better than 0.01 mag) comparable to that of the binaries in our galaxy.

This work triggered many other studies, both in the photometric and the spectroscopic sides. Observations in La Silla, using the 1.52 m Danish telescope, and following the work by Jensen et al. (1988), has resulted in a wealth of accurate uvby light curves within both Clouds, their publication only waiting for accurate spectroscopic radial velocity curves. Although some data are available from observations with the 3.5 m NTT at La Silla, good radial velocities are still the main obstacle for the advance of research in this domain. Binaries are too faint for medium size telescopes and large apertures are needed. Moreover, since the source of accurate dimensions is only provided by well-detached binaries, orbital periods are necessarily long to keep large massive stars separated enough.

Spectroscopic observations have nevertheless been published by Niemela & Bassino (1994) while the first results on absolute dimensions were published by Bell et al. (1991) using HV2226 in the SMC. Unfortunately this system was found to be semi-detached, thus leaving little room for model testing. A similar situation was found in the case of HV5936 (Bell et al. 1993). Spectroscopic observations were obtained using the 3.9 m Anglo-Australian Telescope in Australia.

Photometric studies were also started from Mt. John Observatory in New Zealand using a CCD camera with a modest telescope (Tobin 1994). They discovered the case of the well detached binary HV2274 in the LMC (Watson et al. 1992). This is a very important target due to its eccentric orbit and evidences of apsidal motion which allowed Claret (1996) to establish limits on the masses of the component stars using internal structure constants derived from theoretical models. Radial velocities are now available and accurate absolute dimensions and distance determinations will be published soon (Guinan et al. 1997). Other binaries for which light curves have been obtained include HV12634 (West et al. 1992), HV12484 (Tobin et al. 1993), HV 1761 (Duncan et al. 1993) and the eccentric system HV982 (Pritchard et al. 1994).

Observational difficulties in establishing accurate values of stellar temperatures and interstellar absorption for O−B stars from standard multicolour photometry are moreover being solved thanks to the use of IUE and HST observations in the ultraviolet domain (Guinan et al. 1996). HST observations are also being used by Guinan et al. (1997) to obtain radial velocities in the ultraviolet where numerous spectral features are present.

Although some problems of theoretical and observational nature still remain, tidal evolution of close binary stars can be considered as an additional test to the stellar models. Besides the classical tests of isolated binaries, we can study *critical times* for binaries which are found in clusters. From systematic observations of radial velocity curves of binaries in clusters, some authors (e.g. Mathieu et al. 1992) found a cut-off period ($P_{\rm cut}$) below which the binaries present circular orbits. These critical periods seem to depend on the age of the cluster. Integrating the differential equations for tidal evolution we are able to compare the observed $P_{\rm cut}$ versus age of the clusters with theoretical predictions (see Claret & Cunha 1997, Fig. 5). The time required for eccentricity (or the level of assynchronysm) to decay to 0.05% of its initial value is the theoretical critical time. The ages of the clusters can be considered only as upper limits for the critical time. The investigation of binaries in clusters in the Magellanic Clouds may bring more light on the subject and the necessary tools for such studies in terms of model computations are given in this paper.

On the other hand, the search for gravitational microlensing events is currently providing in a serendipitous way many additional candidate eclipsing binaries in the LMC. The results of both the EROS and the MACHO programs will no doubt increase the sample of good well-detached systems for the study of stellar structure outside of our galaxy. In addition to the mentioned studies, well detached binaries in other galaxies can of course be used as accurate extragalactic distance indicators (Giménez et al. 1994; Guinan et al. 1996).

In this paper we compute the necessary models to compare the accurate data being obtained from detached binaries in the SMC with theoretical predictions. The models thus include values not only for the usual fundamental data (radius, $\log g$, $\log T_{\rm eff}$, $\log L$) as a function of mass, age and initial chemical composition, but also the internal structure constants, $\log k_2$, and other parameters needed for the calculation of predicted levels of orbital circularization and synchronization. In Sect. 2 we present such a grid of models, their main characteristics and the effects of core overshooting and of the initial hydrogen content.

Finally, the need for a grid of models with $Z = 0.004$ is not only given by the study of stars in the SMC but also to allow the interpolation of metallicities in the lower end of the already published series of grids between $Z = 0.01$ (Claret & Giménez 1995) and $Z = 0.03$ (Claret 1997) which was found to be necessary for the LMC and low metallicity binaries in our galaxy.

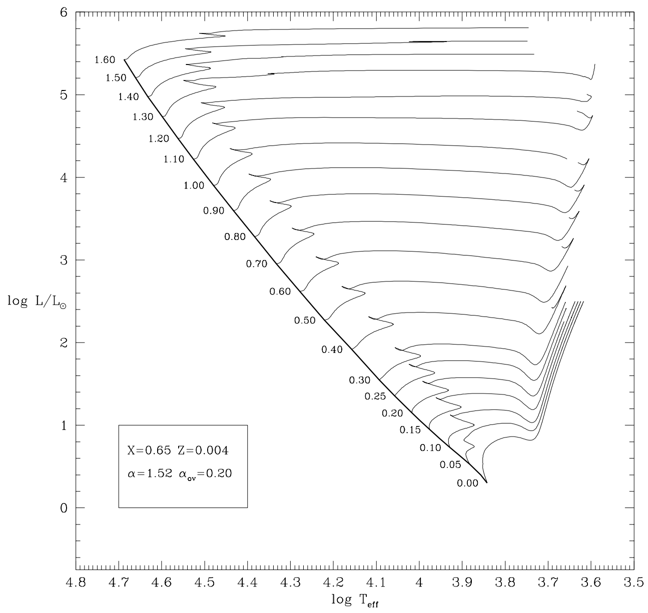

Fig. 1. HR diagram for the grid X65. Numbers attached denote log M

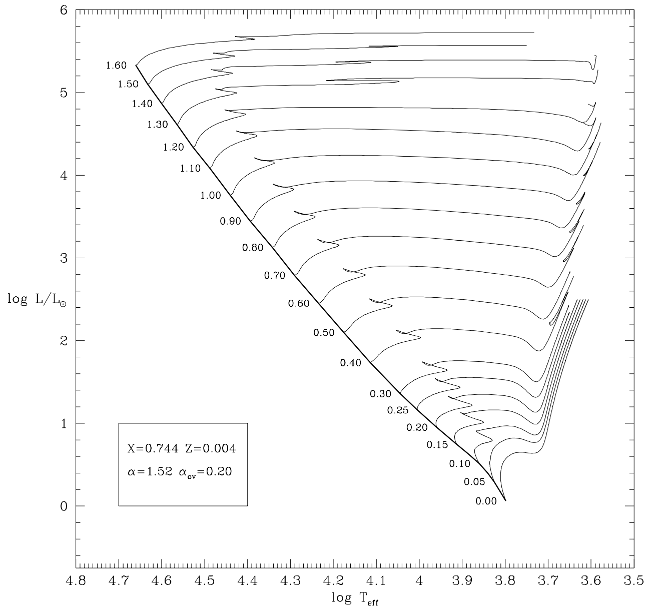

Fig. 2. HR diagram for the grid X744. Same remarks a Fig. 1

3. The grids and the structural parameters

The basic information on the input physics of the models can be found in Claret 1995 (Paper I). The masses of the models shown here range from 1 to 40 $M_\odot$. Convective core overshooting was taken into account for models with $m \geqq 1.25\ M_\odot$. For the adopted initial metal content of $Z = 0.004$, we have computed models with an initial content of hydrogen of 0.65, 0.744 and 0.80. The middle value of 0.744 was selected on the basis of the enrichment law

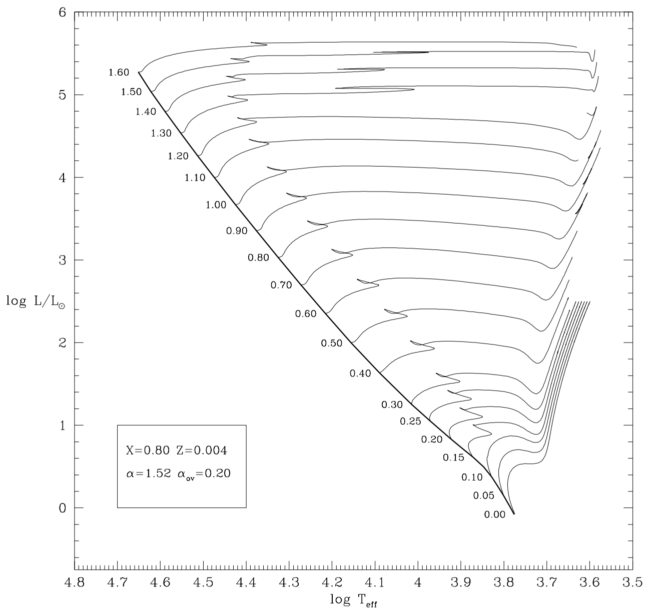

Fig. 3. HR diagram for the grid X80. Same remarks as Fig. 1

$Y = Y_\mathrm{p} + (\Delta Y/\Delta Z)\ Z$ for a primordial helium abundance of 0.24 and an enrichment ratio of 3. The grids with $X = 0.65$ and 0.80 provide the necessary range for parametric studies and interpolation of different chemical composition the latter being obviously artificial from the astrophysical point of view since the corresponding helium content is not compatible with the generally accepted values of the primordial helium abundance. However, it is useful to interpolate the properties of models with intermediary chemical composition.

Figures 1–3 show our usual HR diagrams for the three grids (X65, X744, X80) where the influence of the mean molecular weight on the morphology of the tracks is clear. In fact, by using simple homology relationships it is possible to understand qualitatively the behaviour of radius, effective temperature and luminosity of the models (see previous papers of this series).

The less massive models were computed until just before the helium flash, while the more massive ones were followed up to the core helium burning (in some cases, even until the first stages of carbon burning). However, for the sake of clarity, the blue loops for the more massive models were not plotted in Figs. 1–3. As it is well known, lower metallicity models present more extended blue loops, and we wanted to check their behaviour for fixed values of the mass and the metal content. Figure 4 shows the effect of changing the initial abundance of helium. The extension of the blue loops is presented for different values of initial helium for models of a 6 solar masses star. The blue loops are more extended as the value of Y increases. The existence and extension of blue loops depend on factors such as the central helium burning time scale, the corresponding one for shell burning and, of course, on the available amount

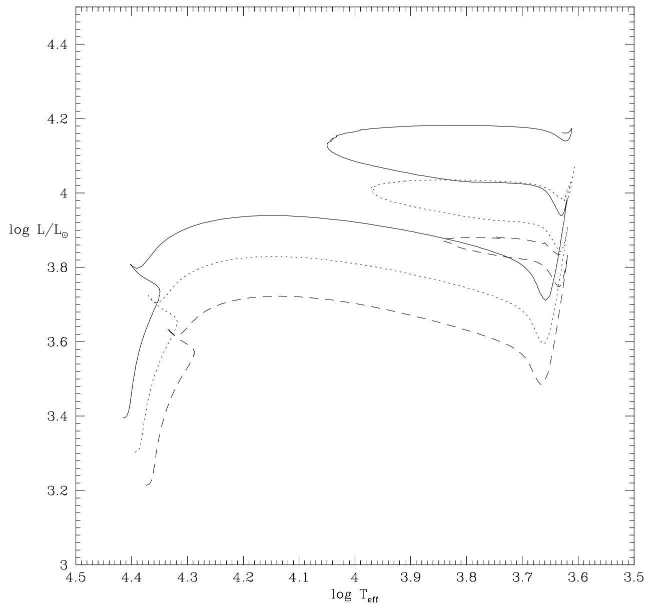

Fig. 4. Influence of helium content in the blue loops. Models with 6 $M_\odot$. Solid line denotes model with $(X,\ Y) = (0.55,\ 0.446)$; dotted indicates $(0.60, 0.396)$ and dashed line represents models with $(0.65,\ 346)$

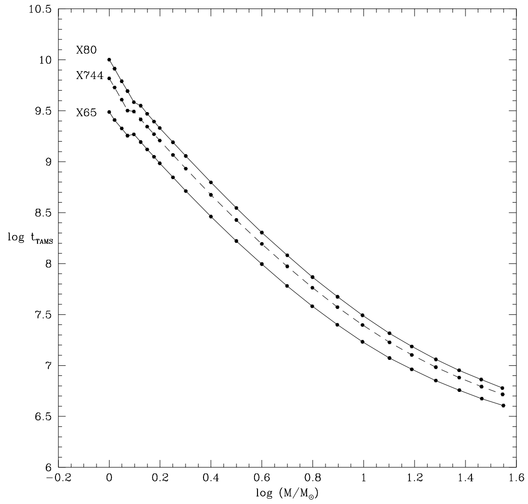

Fig. 5. The lifetimes for the hydrogen-burning phase for the three grids. The grid X65 is represented by a thick continuous line, X744 by a dashed one, and the continuous thin line denotes the grid X80

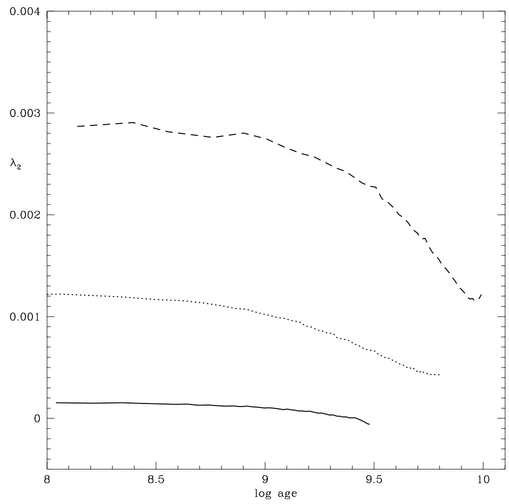

Fig. 6. The parameter λ_2 as a function of the age for models of 1 $M_\odot$ during the main-sequence. The continuous line represents a model with $X = 0.65$, dotted one represents a model with $X = 0.744$ and the dashed line denotes a model with $X = 0.80$

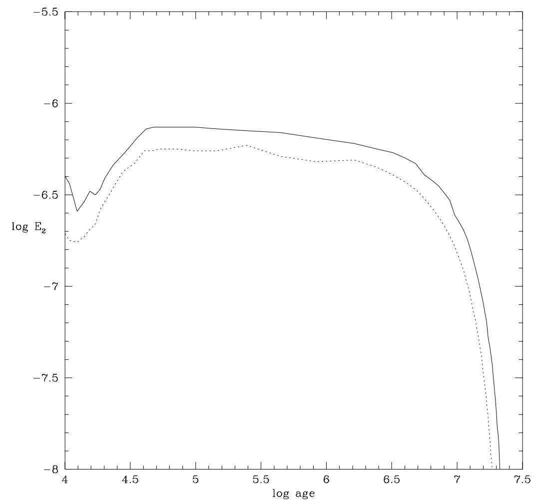

Fig. 7. Effect of the overshooting on the tidal constant E_2 during the main-sequence. Model with core overhooting ($\alpha_{\rm ov} = 0.20$) is represented by continuous line and dashed line denote model without overshooting. Both models are for $X = 0.744$ and the masses are 10 $M_\odot$

of helium. Results shown in Fig. 4 were obtained by integration of the stellar structure equations using a grid of almost 4000 points in order to avoid problems with the chemical composition profiles.

We can see in Fig. 5 the dependency of the main-sequence lifetime on the initial hydrogen content for the three grids presented here. As expected, for a fixed metallicity, the largest lifetime corresponds to the largest initial hydrogen content.

Concerning the structural stellar parameters, we have computed the apsidal motion constants (integrating the Radau equation), the moment of inertia and the potential energy. As commented in Paper II we have also introduced in our stellar evolutionary code the corresponding equations to compute internal parameters which are used to calculate the synchronization and circularizations times in binary systems. These parameters are related with the equilibrium and the dynamical tides. In the case of the equilibrium tides the turbulent dissipation was identified as the agent of synchronization and circularization of orbits in binaries presenting convective envelopes. In order to compute the time scales for synchronization and circularization, we have to calculate the constant λ_2 which depends on the physical properties of the stellar envelope. Indeed, following the mixing-length approximation, the constant λ_2 can be written as (Zahn 1989)

$$\lambda_2 \propto \int_{x_b}^{1} x^{22/3}(1-x)^2 \mathrm{d}x \quad (1)$$

where x_b indicates the bottom of the convective envelope in normalized units. Some years ago, the apsidal motion constant k_2 was used instead of λ_2. As we have shown in previous papers (Claret & Cunha 1997, Fig. 3 and in the Paper II, Fig. 9) this is a good approximation, at least during the Main-Sequence. Figure 6 shows how λ_2 depends on the chemical composition. Since this parameter depends on the depth of the convective envelope, the hydrogen content drives its behaviour. It is interesting to note that within the mixing-length theory the differences due to changes in the initial chemical composition can reach almost an order of magnitude.

The mechanism used to investigate the tidal evolution of stars with convective core and radiative envelopes is the radiative damping which is characterized by the tidal torque constant E_2. The calculation of such a parameter is more problematic since it depends, among other intermediary calculations, on the derivative of the Brunt-Väisäla frequency just in the boundary of the convective core. For little evolved models, near the ZAMS, the computations are relatively simple. When a star in these conditions evolves, the convective core recedes and a large chemical composition gradient appears. Such gradients are responsible for the numerical difficulties to compute the tidal torque constant.

As E_2 depends strongly on the physical conditions just at the boundary of the convective core, one should expect differences between models with and without core overshooting. Figure 7 illustrates the situation for models with 10 $M_\odot$. The model computed adopting core overshooting present values of E_2 slightly larger than the standard one (about 0.1 dex as a average). This difference is not distinguishable at the present data quality of synchronization and circularization levels.

In order to maintain a coherent format with respect to the previous models of this series published in the WWW page of CDS at Strasbourg the values of λ_2 and E_2 are not given. Interested readers can send their request sending a message to claret@iaa.es.

Acknowledgements. The Spanish DGYCIT (PB94-0007 and PB96-0840) is gratefully acknowledged for support during the development of this work.

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