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Stellar models for a wide range of initial chemical compositions until helium burning.*,** I. From X=0.60 to X=0.80 for Z=0.02

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Abstract. — New grids of stellar evolutionary models are presented for a wide range of initial hydrogen content around the solar composition. These compositions are (X, Z) = (0.80, 0.02), (0.70, 0.02) and (0.60, 0.02). Recent OPAL opacities with LS coupling and Grevesse composition were adopted, and Alexander's tables were used for lower temperatures. We consider models with core overshooting with α_{ov}=0.20, and mixing length parameter l/H_p=1.52 that seems to represent well double-lined eclipsing binary stars. Mass loss during the main sequence and in the red giant phase were taken into account. The nuclear network treats 14 isotopes and optionally the lithium burning to study its depletion in less massive models during pre main sequence evolution. The mass range covered goes from 1 up to 40 $M_\odot$ and the more massive models were followed until helium burning. The main aim of the present series of papers is, besides the inclusion of the new opacities, to explore the effects on different outputs of the stellar models, of a change of the helium content at a given metallicity. We also present isochrones in the plane log g − log M which are very useful to compare the best parameters known for binary stars (masses and radii) with theoretical predictions. The internal structure constants for apsidal motion investigations are also presented.

Key words: stars: binaries: general; evolution; interiors; fundamental parameters — abundances

1. Introduction

Binary stars are our best source of knowledge of stellar masses and radii. Due to the high accuracy of these parameters, double stars become the best test to the evolution theory. During the last few years we have investigated the internal structure of stars by means of the analysis of double-lined eclipsing binaries (DLEB) exhibiting apsidal motion. This is possible by joining spectroscopic and photometric data obtained with great accuracy since the apsidal motion constant k_2 in DLEB depends strongly on the stellar radius as R^{-5}, as well as on the masses, periods and eccentricities.

The main objective of stellar astrophysics and in particular of the astrophysics of DLEB is to test the evolution theory. In such a way, stellar models concerning DLEB showing apsidal motion must pass rigorous tests before direct comparison between observed and predicted k_2. In few words, the tests consist in (for more details, see Claret & Giménez 1993a,b)

1. verifying whether the components of the systems are on the same isochrone for the same chemical composition
2. comparing observed and predicted effective temperatures as derived from observed masses and radii
3. investigation of the observed rotational velocities to take into account the contribution of rotational distortions to measured apsidal motion.

If these criteria are fulfilled, we will be able to compare observed and theoretical values of internal structure constants. We should recall that studies of synchronization and circularization are also dependent on the same tests if one wants to obtain information of good quality on the interior of the stars.

To probe stellar models using DLEB (and in other studies too) another equally important piece of information is required: the chemical composition. Unfortunately, this information is not easy to obtain. For some F-type eclipsing binaries stars (Andersen et al. 1988, 1989) we have determination of the metallic content and there is a project to measure metals in components of binary stars (Clausen 1993). Moreover, we should not forget that hydrogen and helium compositions are equally important.

*Tables 1-74 are available in electronic form at the CDS: see the Editorial in A&AS 1994, Vol. 103, No. 1

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Knowledge of the metallicity does not imply that the problem is solved uniquely, given the uncertainties involved in the laws relating the enrichment in helium to that in heavy elements.

Stellar models are available in a broad range of metallicities but, for a given initial metallicity, usually only one set of models with one helium content value is computed. In the most recent of our papers on stellar models we adopted for the helium enrichment $Y = Y_p + (\Delta Y/\Delta Z)Z$ where Y_p is the primordial helium. The currently adopted value for Y_p is around 0.24. Audouze 1987 quoted a ^{4}He content in his Table 1 for the solar system and interstellar medium. Extreme values are between 0.17 for the solar system and 0.30 for the interstellar medium. However, for Saturn and Jupiter the results should be taken with care. In fact, gravitational settling could play a significant role, and the helium content for these planets may not be representative for the solar system. The proceedings of the ESO workshop on primordial helium (1983) contain several papers in which the ^{4}He content is significantly spread. Nissen 1983, for example, using young clusters, found variations as large as 0.10 between one cluster and another. Extragalactic HII regions can be used to study primordial helium. More recently Pagel et al. 1992 found that Y_p is around 0.228. Comparing this estimate with other sources of information on primordial helium we may infer an average error around 5−10%.

These uncertainties reflect directly upon the adopted helium content and consequently in the models. But the main source of uncertainty surely comes from the enrichment laws. Maeder 1983a reports some sources of uncertainty in the ratio $\Delta Y/\Delta Z$, such as low initial metal content, mass transfer in binary systems and mixing process. Modern estimates for HII galactic regions indicate that there is indeed a broad range of values (2.04 up to 5.74) and Peimbert 1993 illustrates this fact.

On the other hand, this derivative can be inferred from the calibration of the Sun as well as from the mixing length parameter. Improvements in opacities change these value significantly (Schaller et al. 1992 p. 270). Summarizing, besides the difficulties of chemical composition measurements, the uncertainty in the primordial helium and in the laws of enrichment, opacity uncertainties pose an additional problem. Wider grids in chemical compositions will allow the influence of different mixtures to be investigated and may help us to establish theoretical error bars.

2. Physical ingredients and the grids of models

The computer code is basically the same as that described in our previous works (Claret & Giménez 1989, 1991, 1992) but we recall some of the basic properties. The four differential equations are solved by means of the Henyey method and about 400−700 points mesh points in the interior were used. A gray atmosphere model is used, and integration in τ were carried out from 2 up to 1 10^{-4}.

Mass loss rates were taken from Nieuwenhuijzen & de Jager (1990) for models with initial mass above 10 $M_\odot$ during the main sequence while the formalism by Reimers (1977) was considered for more advanced stages of evolution. Core overshooting was considered as quoted in our previous papers. The parameter for the mixing length theory is 1.52, and for core overshooting we adopted α_{ov} = 0.20 which seems to represent well binary stars with a good determination of absolute dimensions (see Claret & Giménez 1992, 1993a, 1993b). The chemical composition and the mixing lentgh parameter derived for the Sun were little sensitive to new LS opacities with respect to the 1992 calibration.

We used the new set of opacities provided by Iglesias et al. 1992 with spin-orbit coupling. These new tables cover a larger range in temperatures and mainly in R (ρ/T_6^3). For stellar envelopes where the temperatures are around and below 6000 K (which is the minimum temperature in OPAL tables) we used Alexander's results. Los Alamos (Huebner et al. 1977) tables were used in the range not covered by OPAL calculations. All opacity tables used, no matter their limits in temperatures and densities, are based on the Grevesse (1991) determination for the solar photosphere composition.

A slightly more extensive nuclear network was used. We decided to include some isotopes and we now treat 14: H, ^{2}H, ^{3}He, ^{4}He, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O (or ^{18}O), ^{20}Ne, ^{24}Mg, ^{28}Si, ^{56}Ni (or ^{56}Fe). The hydrogen network treats the three pp-chains and the CNO cycle (see Maeder 1983b). For the helium burning we used the following reactions

$^4\mathrm{He}(\alpha,\gamma)^8\mathrm{Be}(\alpha,\gamma)^{12}\mathrm{C}(\alpha,\gamma)\ ^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$

During helium burning, the ^{14}N, product of the CNO cycle reacts with α-particles. Since the energy released by the reactions $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\mathrm{e}^+,\nu)^{18}\mathrm{O}(\alpha,\gamma)\ ^{22}\mathrm{Ne}$ does not contribute significantly to the energy generation, they are only used when a more detailed nucleosynthesis is required (in this paper the computations are interrupted during the first stages of the helium burning). The β-decays , the abundance of ^{2}H and (^{7}Li+^{7}Be) are assumed to be in equilibrium. The screening factors were taken from Graboske et al. (1973), and the neutrino loss rates are from Munakata et al. (1985). The nuclear rates were taken from Fowler et al. (1975) Harris et al. (1983) Caughlan et al. (1985) and Caughlan & Fowler (1988). The time step was controlled by a subroutine that uses some criteria of convergence of the preceding model. For example, depending on the relative change of the isotope, the time step is increased or decreased. This and other tests have been performed for each shell in the interior where nuclear burning is active. A few tests were applied to the problem posed by Schaller et al. (1992) on the convenience of adopting the explicit or implicit method when nuclear network is operating. Within the expected differences between our models and those by Schaller et al. (recall that we use a

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slightly different set of isotopes) we do not find significant differences in the isotopes content in the center of both models. To realize this comparison we computed a model with 12 $M_{\odot}$ with the same chemical composition, that is, X =0.680 and Y=0.300.

Partial ionization was taken into account through Saha's formalism, as well as by using gas and radiation pressure and Fermi-Dirac integrals when necessary. We carried out some tests using alternative equations of state such as MHD (Hummer & Mihalas 1988; Däppen et al. 1988, Mihalas et al. 1988). This equation of state is based on a free-energy minimization method which considers: a) translational motion of classical particles; b) internal excitation of molecules, atoms and ions; c) translational motion of partially degenerate electrons and, d) coulombian interaction. In the range of masses considered here the parameters log L, log $T_{\rm eff}$, log g, the nuclear burning and the apsidal motion constants have not changed significantly. However, depending on the mass and effective temperature ranges, the use of different equations of state may yield different values for the mixing length parameter and/or initial helium content. Coulombian-pressure correction is one of the non ideal gas effects which is important for models with masses lower than 1 $M_{\odot}$. We have used the so-called CEFF equation of state (Christensen-Dalsgaard 1991; Christensen-Dalsgaard & Däppen 1992) only for models with 0.8 and 0.6 $M_{\odot}$ (X=0.70, Z=0.02). This equation is a new version of the EFF (Eggleton et al. 1973) equation of state which incorporates the coulombian interaction in the Debye-Hückel approximation. In helio and asteroseismological studies, the influence of the equation of state is important, for example when determining the sound velocity in the outer layers. In this case, more elaborate formalisms are preferred (Christensen-Dalsgaard & Däppen 1992; Däppen 1993).

The apsidal motion constants are calculated for every initial mass stars and for all evolutionary time steps. This is carried out by integrating the differential equation of Radau

$$\frac{r\mathrm{d}\eta_j}{\mathrm{d}r}+\frac{6\rho(r)}{\overline{\rho}(r)}(\eta_j+1)+\eta_j(\eta_j-1)=j(j+1),\quad (j=2,3,4) \tag{1}$$

and the corresponding values which leads to the apsidal motion constants as given by

$$k_j=\frac{j+1-\eta_j(R)}{2\,(j+\eta_j(R))} \tag{2}$$

where $\eta_j=\frac{\mathrm{dln}\epsilon(r)}{\mathrm{dln}r}$, $\epsilon(r)$ describes the deviations of the equipotential surfaces from spherical symmetry and R is the radius of the configuration. The functions η_j are zero in the center of the star. The local density is $\rho(r)$ and $\overline{\rho}(r)$ is the mean density at distance r. The three equations were integrated through a Runge-Kutta method of fourth order. The size of the integration step was checked by computing the same models with more points. If a reasonable number of points are provided, we do not find significant differences.

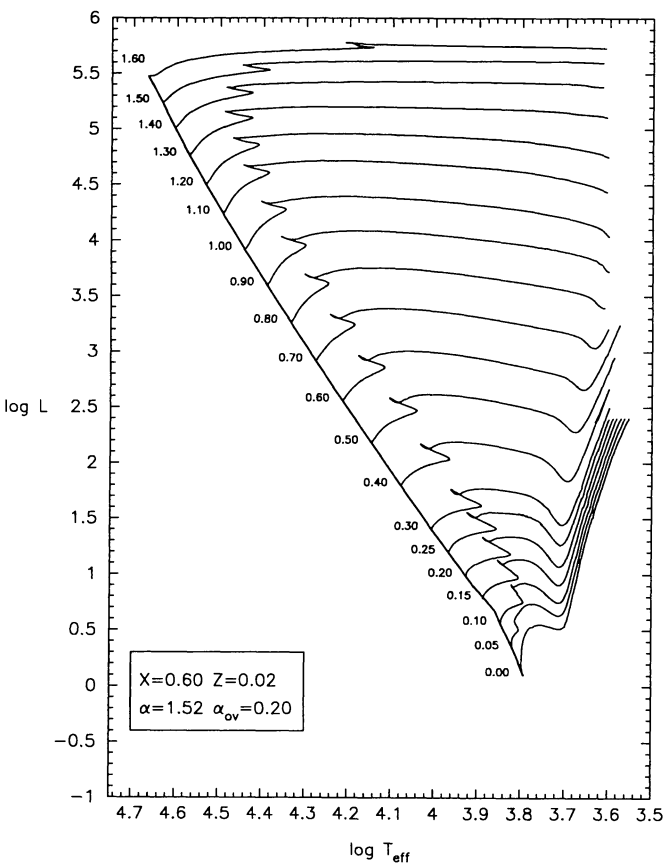

Fig. 1. HR diagram for the grid X=0.60, Z=0.02. The attached numbers denote log M

The radius of gyration is an important parameter when dealing with synchronization and circularization of orbits in close binary stars. The times scales for both phenomena are strongly dependent on the stellar radius. Through correlated parameters namely rotational velocities and eccentricities it is also possible to gain insight on the stellar interiors. Actual eccentricities and rotational velocities act like a limit in the confrontation between predicted circularization and synchronization times and derived ages. The radius of gyration β is calculated using the same method as for apsidal motion constants. The potential energy Ω is also computed, and is related with the so-called α as $\Omega = -\alpha \mathrm{GM}^2/R$.

The models presented here cover the mass range between 1 and 40 $M_{\odot}$. The three chemical compositions are (X, Z) = (0.80, 0.02), (0.70, 0.02) and (0.60, 0.02). Models for $Y_{\rm initial}$ = 0.28 were re-calculated since new opacities with spin-orbit coupling (Grevesse 1991 mixture) were used instead of our previous grid of 1992 which considered no LS coupling and Anders & Grevesse's 1989 mixture.

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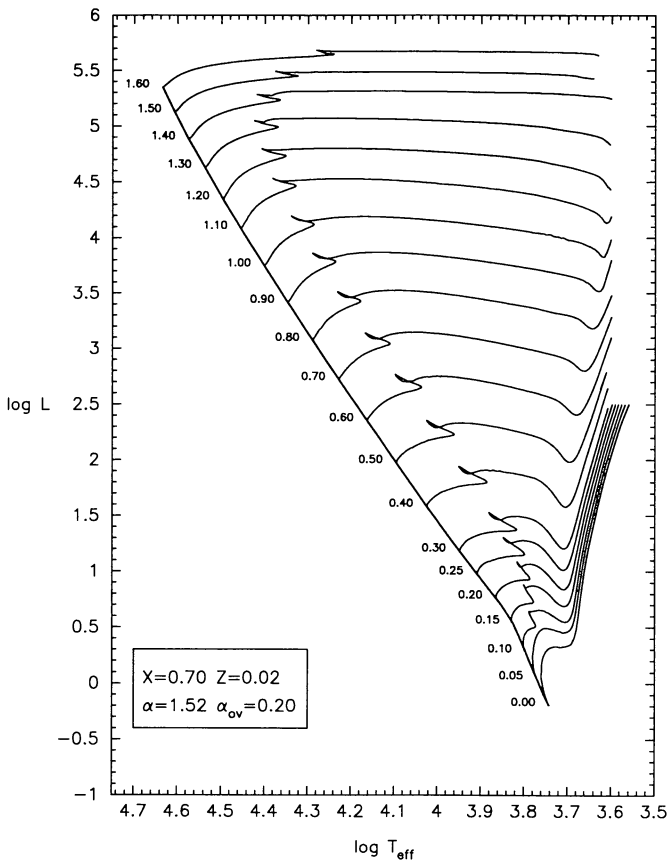

Fig. 2. The same as Fig. 1 for chemical composition X=0.70, Z=0.02

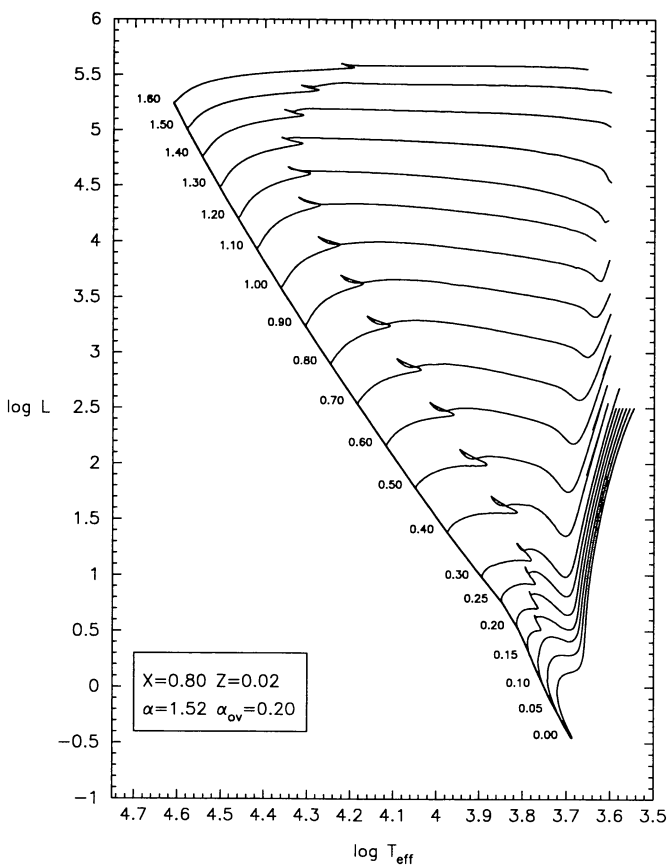

Fig. 3. The same as Fig. 1 for chemical composition X=0.80, Z=0.02

Figures 1, 2 and 3 show the HR diagram in its log L–log $T_{\rm eff}$ form. By using very simple approximations, we can get a reasonable picture of the change of the hydrogen content in the model outputs, namely, luminosity, radius and effective temperatures. Following Schwarzschild (1958), the stellar radius depends on the mean molecular weight as μ^{ν} and the effective temperature as μ^{λ} where ν and λ are larger than zero. Since the three grids are symmetrical with respect to the hydrogen content, we will center our attention on the models with (X, Z)=(0.60, 0.02) and (0.70, 0.02), hereafter X60 and X70, respectively. For a fixed mass, an increase of hydrogen content implies a lighter mean molecular weight and reduces the effective temperature and luminosity. Indeed, the X60 models are systematically hotter and brighter, at a given mass, than the X70 models.

With respect to Figs. 4, 5 and 6 we can recognize similar features. These diagrams reflect the increase of the width of the main sequence with the increase in hydrogen content. The main sequence lifetime ratio ($\tau_{\rm X70}/\tau_{\rm X60}$) is around 1.6 and it is even larger for less massive models. On the other hand, for a given value of the effective temperature, the X60 models present radii larger than the X70 set.

The effects of changing the chemical composition on the apsidal motion constant during the main sequence ($X_{\rm c}$ $\approx$ 0.01) are illustrated in Fig. 7 for some selected models. For ΔY=$\pm$0.10, the respectives changes in log k_2 are of the order of $\pm$0.02 though, for more massive models, the changes are smaller. The differences become larger as the models evolve, for a given mass.

There are many cases of DLEB for which a good determination of effective temperatures does not exist. This is the case, for example, when the measurements available are not very good or when problems arise with the calibration of $T_{\rm eff}$-colour indices. However, if the masses and radii are of good quality the evolutionary models may help to elucidate certain problems concerning, for example, the position of the system in the HR diagram. In order to do this, we can use isochrones in the plane log g–log$M$. A good illustration of this fact is provided in the case of CC Cas (Hill et al. 1994).

Tables containing basic informations about the tracks which allow calculation of isochrones and/or direct comparison with observations are available through FTP and electronic mail (aclaret@iac.es).

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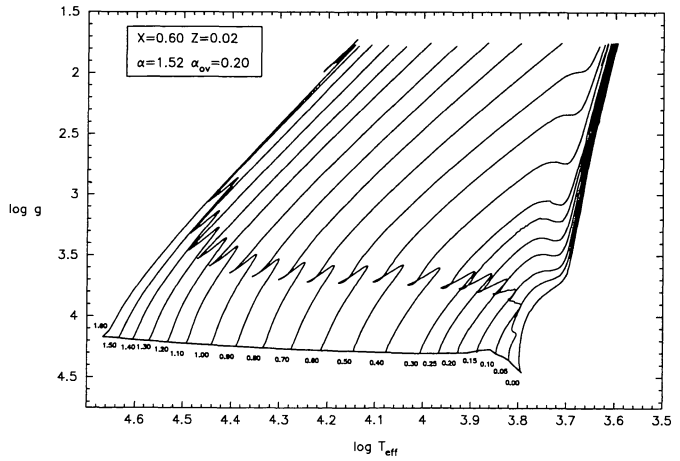

Fig. 4. Log g − log $T_{\rm eff}$ diagram for the grid X=0.60, Z=0.02. The attached numbers denote log M

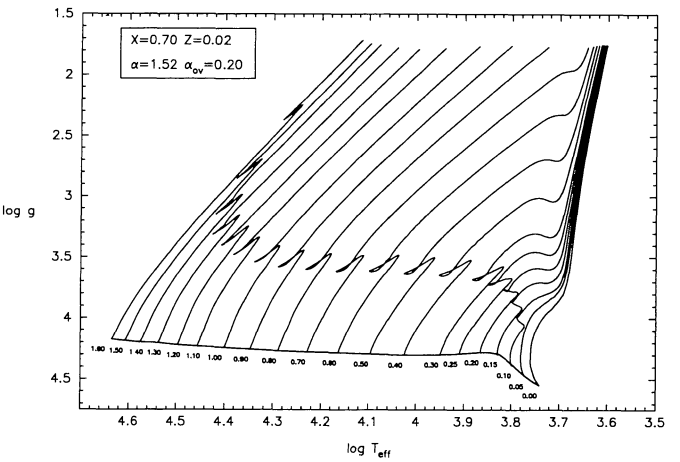

Fig. 5. The same as Fig. 4 for chemical composition X=0.70, Z=0.02

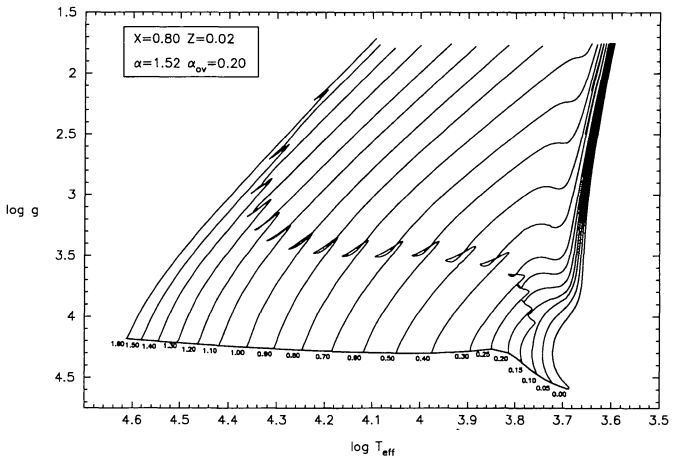

Fig. 6. The same as Fig. 4 for chemical composition X=0.80, Z=0.02

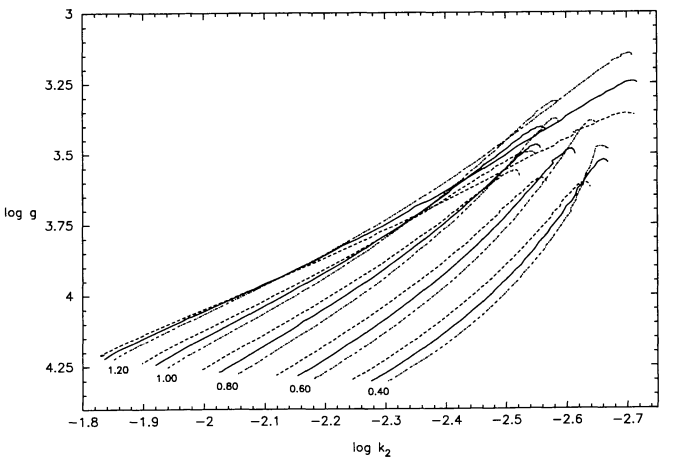

Fig. 7. The effects of chemical composition on the internal structure constant log k_2 during the main sequence. Full lines represent models with X_i=0.70; dashed lines, models with X_i=0.60; dash-dotted lines denote models with X_i=0.80. Numbers below the tracks indicate log M

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