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ASTRONOMY AND ASTROPHYSICS

α Centauri and convection theories

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Abstract. The metallicity of the alpha Centauri system, Z, suffers from uncertainties. For this reason, different methods are used to calibrate the system: calibrations performed in YALE (Edmonds et al. 1992) use a fixed value for Z: Z= 0.026 and a convection parameter for each star, while those made in Meudon and Liège (Noels et al. 1991; Neuforge 1993a) make the hypothesis of a unique convection parameter for the two components of the system and consider Z as a free parameter. We discuss these two techniques, both using models calculated with mixing length convection theory, (MLT), and we explain our solution through the behaviour of the convection parameter with chemical composition. We also compare our results with those of Lydon (1993) and find consistency. With a precise observational value of Z, of the effective temperatures and of the luminosities, our results provide a test for the unicity of α, if, in the frame of the same physics, a precise atmosphere treatment can be used and low-temperature opacities are known with sufficient accuracy.

Finally, we perform calibrations with models calculated with the convection treatment of Canuto & Mazzitelli (1991, 1992), where we use Λ = z, z being the distance to the top of the convective envelope. We avoid thus problems raised by the MLT convection parameter. In this frame, satisfactory solutions can be found for $0.024 \leq Z \leq 0.040$.

Key words: stars: α Cen – stars: fundamental parameters – stars: interiors – convection

1. Introduction

α Centauri is the closest binary system. So, masses and luminosities of its two components, α Cen A and B are known with a rather good accuracy (see Noels et al. 1991): M_A= 1.085 $M_\odot$
M_B= 0.900$M_\odot$
$Log(\frac{L}{L_\odot})_A$= 0.1853 ± 0.015 $Log(\frac{L}{L_\odot})_B$= -0.3065 ± 0.015

Effective temperatures can be determined through spectroscopic analyses. These values are still somewhat uncertain. We have adopted the most recent values given by Chmielewsky et al. (1992):
Te_A= 5800 ± 20K Te_B= 5325 ± 50K
Many attempts have been made to derive observationally the metallicity of the α Centauri system. Some authors derived Z= 0.026 (Furenlid & Meylan 1990), while others found higher values, around Z=2$Z_\odot$ (French & Powell 1971; England 1980; Edvardson 1988). The most recent values are those of Meylan et al. (1992), which are a revision of the results of Furenlid & Meylan (1990), and those of Chmielewsky et al. (1992). Their values are:

$log(\frac{Z}{Z_\odot})$ = +0.20	Meylan et al. (1992)
$[\frac{Fe}{H}]_{\alpha CenA}$ = +0.22 ± 0.02	Chmielewsky et al. (1992)
$[\frac{Fe}{H}]_{\alpha CenB}$ = +0.26 ± 0.04	Chmielewsky et al. (1992)

This means that $[\frac{Z}{X}]$(= $log\frac{(\frac{Z}{X})_{star}}{(\frac{Z}{X})_\odot}$) takes values within 0.2 and 0.3.

The Z-value derived from α Cen A should be more reliable than that derived from α Cen B since the first star has an effective temperature closer to that of the Sun, making the differential analysis with the Sun more accurate (Chmielewsky 1994). The age t of the system and its helium abundance Y remain unknown. Because of the uncertainties, the metallicity of the system, Z, may also be taken as a free parameter. If convection is treated in the frame of the mixing length theory, the convection parameter, α, ratio of mixing length to pressure scale height in convective layers, can also be adjusted. These parameters can be derived through a calibration of the system. Nevertheless, a problem arises about the possible unicity of the convection parameter in both stars. The unicity of α in solar-type stars has to be tested for the following reasons:
a) calibrations of binary systems of such stars require the hypothesis of a unique α if their metallicity is unknown;
b) if α is obviously non unique for solar type stars, isochrones and models of non solar-type stars may not be calculated with the solar calibrated α-value.

The problem of α is a very puzzling one since it has become progressively more and more clear that resetting α not only

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resets the approximations intrinsic to the MLT; it also helps in hiding under the rug other physical uncertainties: mainly those in the opacities and in the thermodynamics.

2. Calibrations using mixing length convection theory

Calibrations made in Meudon and in Liège (Noels et al. 1991; Neuforge 1993a) were performed with the Liège stellar evolution code initially developed by Henyey et al. (1964). The convection treatment is based on the work of Henyey et al. (1965). These calibrations make the hypothesis of a unique convection parameter, α, for the two components of the system. So, four parameters, t, Z, Y, and α are adjusted to give the best fit between the evolutionary tracks and the observed luminosities and effective temperatures.

With the Debije-Huckel corrections in the equation of state (Noels et al. 1984), a treatment of the photospheric layers taken from Krishna Swamy (1969), the interior opacities of Rogers & Iglesias (1992) and the low-T opacities of Neuforge (1993b), our solution is:
Z= 0.038 Y= 0.322 t= 4.84 Gyr α= 2.10
This solution is clearly in favour of a high metallicity. To calculate our models, we used the abundance distributions of Grevesse & Noels (1993), which result from their new C, N, O abundance determinations in the Sun. They find $(\frac{Z}{X})_\odot = 0.0245$. With this value, their calibration of the Sun leads to $Z_\odot$= 0.01756, $Y_\odot$= 0.266 and $\alpha_\odot$= 2.06. The values of α in the Sun and in α Centauri are very close.

2.1. *Unicity of the convection parameter*

Calibrations performed at YALE (Edmonds et al. 1992) do not adopt the hypothesis of a unique α but are made for a fixed Z-value: Z= 0.026 (Furenlid & Meylan 1990). These calibrations proceed in two steps:

1) Using $\alpha = \alpha_\odot$, two parameters, t and Y are determined so that the calculated luminosities fit the observed values at the same age.

2) The two convection parameters are then adjusted to reproduce the observed effective temperatures.

For their models without diffusion, their solution is:
Z=0.026 Y= 0.300 t= 4.7 Gyr α_A=1.06 α_B=1.251
We have performed such calibrations for different values of Z, using the same physics as in our previous calibrations with a unique α. Our results are presented in Table 1:

Table 1. Results obtained from our calibration with fixed Z-values. The values in brackets result from the effects of the uncertainties affecting the luminosities

Z	t(Gyr)	Y
0.020	5.10 [7.14,3.17]	0.267 [0.249,0.285]
0.026	5.62 [7.20,4.00]	0.285 [0.271,0.300]
0.030	5.93 [7.17,4.21]	0.296 [0.284,0.312]
0.038	5.72 [7.41,4.05]	0.318 [0.301,0.334]
0.040	5.61 [7.34,4.56]	0.324 [0.306,0.333]
Z	α_A	α_B
0.020	1.74 [2.00,1.51]	2.03 [2.39,1.75]
0.026	1.91 [2.10,1.70]	2.10 [2.40,1.89]
0.030	2.03 [2.19,1.81]	2.18 [2.40,1.90]
0.038	2.10 [2.32,1.90]	2.13 [2.50,1.89]
0.040	2.11 [2.34,1.98]	2.09 [2.45,1.96]

2.1.1. Behaviour of α as a function of Z

Except for a solution around Z $\sim$ 0.039, it is clear that, *for our adopted luminosities and effective temperatures*, all the other Z-values lead to different α-values. Figure 1 shows α_A and α_B as a function of Z, in our models and in those of Lydon et al. (1993), together with the values we obtained with the effective temperatures adopted by Lydon et al. (1993).

In our models, after an increase in α for both components as Z increases, a maximum is reached for α Cen B whereas an inflexion is only visible for α Cen A. The crossing of the two curves occurs near Z= 0.039 and reflects, at first order, the solution we obtained in Sect. 2 with our hypothesis of a unique α value. This behaviour of the convection parameter results from the effects of chemical composition on the opacity at the lower temperatures.

2.1.2. Effects of chemical composition on the opacity

In our calibrated models, high metallicities are associated with low hydrogen abundances. These two parameters are important contributors to the opacity; the metallicity affects essentially the stellar photosphere, while the hydrogen content plays a crucial role in the non adiabatic part of the convective envelope.

a) Effects of Z

In the radiative photosphere, an *increase of* Z leads to higher opacities since the opacity, κ, is dominated by H^- absorption and at temperatures encountered in that region, electrons needed to form H^- come from heavy elements. A higher opacity in the photosphere leads to a higher radiative temperature gradient, ∇_{rad},and thus to a lower effective temperature.

Let us first neglect the change in X which would affect the opacity in the non-adiabatic part of the convective envelope (see b). In order to restore the effective temperature, the α-value must be adjusted, with the constraint that the total luminosity should remain equal to the observed value. An *increase of* α implies a lower temperature gradient ,∇, in order to keep the total luminosity constant, as it is shown by the following relations:

$$L_{rad} \sim \frac{\nabla}{\kappa} \tag{1}$$

$$L_{conv} \sim \alpha^2 (\nabla - \nabla_{ad})^{3/2} \tag{2}$$

$$L_{tot} = L_{conv} + L_{rad} \tag{3}$$

where L_{rad}, L_{conv} and L_{tot} are respectively the radiative, convective and total luminosity, and ∇_{ad} the adiabatic gradient. Thus, a higher α-value leads to a higher effective temperature, as a consequence of the decrease in ∇ , compensating for the

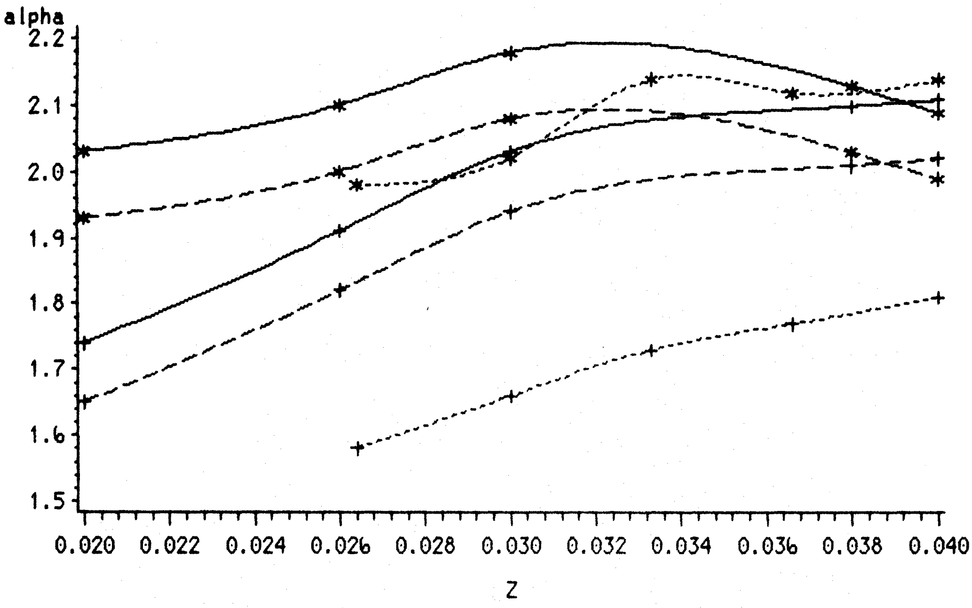

Fig. 1. α_A (crosses) and α_B (stars) as a function of Z as derived: a)from our calibrations with our adopted effective temperatures (solid lines) and with the effective temperatures adpoted by Lydon et al. (1993; dashed lines); b) from the calibrations of Lydon et al. (1993; dotted lines)

decrease in Te resulting from the metallicity effect on the opacity in the photosphere.

b) Effects of X

Now, a *decrease of X* (associated with an increase in Z) does actually affect the opacity in the non-adiabatic part of the convective envelope. In these layers, bf and ff transitions of H and He are the main contributors to the opacity, which then decreases as X decreases. The relations 1 to 3 show that, in this region, a smaller opacity must be compensated by a *lowering of* α , keeping ∇ and thus Te constant.

c) Global effects

In our calibrated models, and for our adopted luminosities and effective temperatures, the behaviour of the opacity with chemical composition leads to opposite effects on α. Firstly, in the photospheric layers, higher opacities resulting from higher Z-values lead to an increase in α. However, the variations of these opacities become less important as Z increases. Then, in low X models, the lowering of opacity in the non-adiabatic part of the convective envelope play a more important role in the behaviour of α , which now decreases or increases less rapidly. For a Z-value close to 0.039 the convection parameters reach the same value for both stars, close to the solar one, while for other Z-values, they are different. Now, it is understandable why our calibrations made with a unique α-value for both components lead to a Z-value around 0.039.

Figures 2 and 3 show the effects on the convection parameters of the observational uncertainties affecting the effective temperatures and the luminosities. It can be seen from these figures that:
a) the resulting maximum or the inflexion in the (α, Z) curve depend on the effective temperatures and thus crossing in the curve for α Cen A and α Cen B can occur for Z-values down to 0.22;
b) the uncertainties affecting the observed luminosities imply that, for each fixed Z-value, a possible range in X-values and thus in α_a and in α_b can be found. Because of the different X-values, the behaviour of the convection parameters may differ slightly from that described in Sect. 2.1.2.

These uncertainties must be added together and the resulting range of possible α_A and α_B is too large to be compared to the solar calibrated value. New data from Hipparcos will probably substantially reduce the uncertainties affecting the luminosities and thus their effects on α.

It should also be noted that even in the Sun, where L and Te are observationaly very well constrained, the uncertainties affecting low-T opacities imply that the solar convection parameter cannot be determined with an accuracy greater than a few percents. This has been demonstrated by Sackmann et al. (1990), who studied the effects of a variation of low-T opacities on α.

We also attempted to constrain, for each fixed Z, the helium content of the α Centauri system, through the comparison of our results with the observational values of the ratio $\frac{\Delta Y}{\Delta Z}$. Unfortunately, these values are still very controversial (Wilson & Rood 1994) and are obtained by observing low metallicity HII regions. The possible metallicity dependence of the yields of heavy elements (Pagel 1994) implies that these observational values may not be extrapolated to Z-values higher than solar.

2.1.3. Comparisons with other calibrations

In a comparison between the results of different calibrations, the physics used as well as the adopted observational data must be taken into account.

For Z = 0.026, Edmonds et al. (1992) find Y=0.300 for their model without diffusion, instead of our 0.285 value. However, they did not consider the Debe-Huckel correction in the equation of state, they used the interior opacities of Los Alamos (Huebner et al. 1977) and adopted different luminosities. We

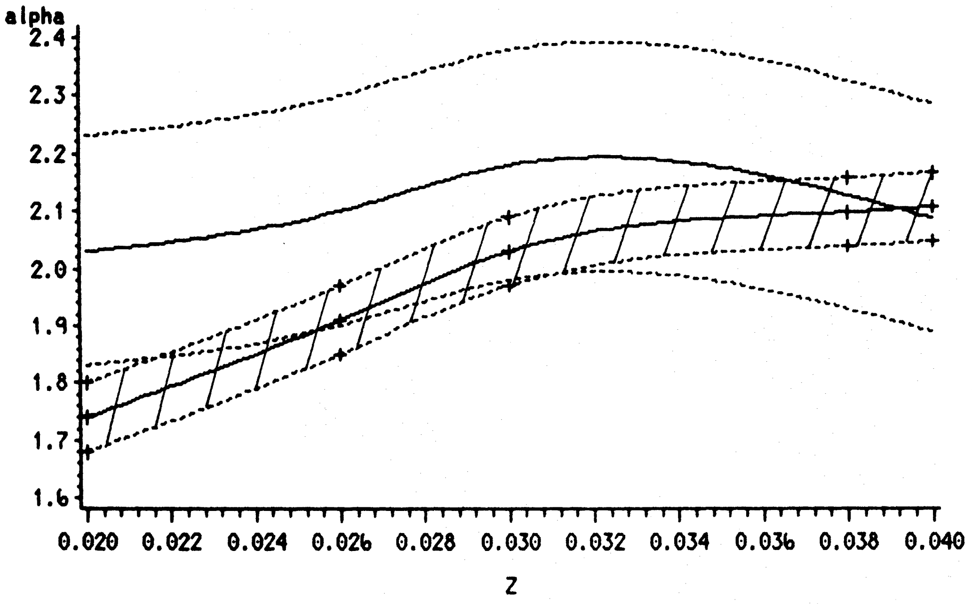

Fig. 2. α_A (crosses) and α_B as a function of Z as derived from our calibrations (solid lines). Dotted lines show the effects of the uncertainties affecting the effective temperatures of both star

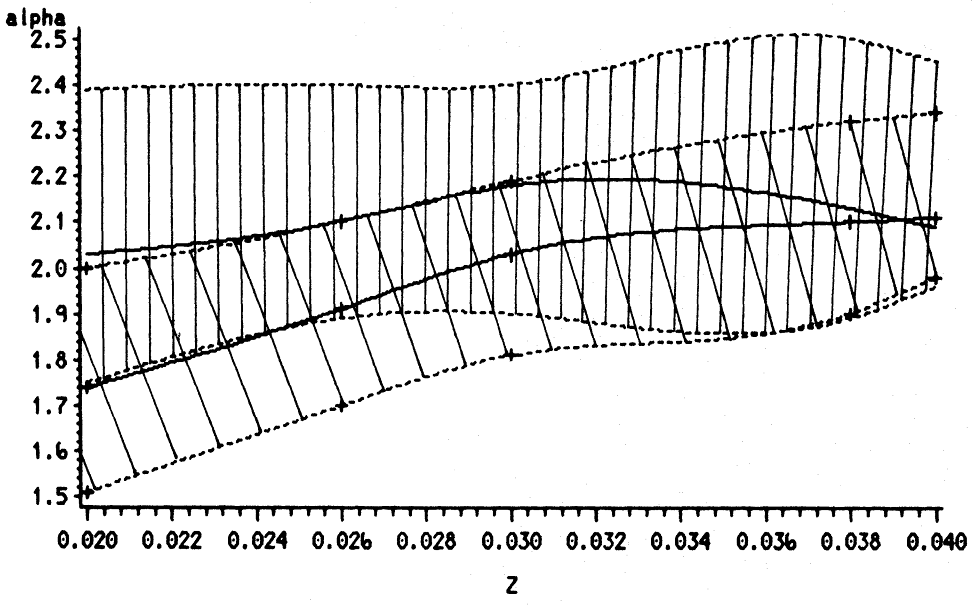

Fig. 3. α_A (crosses) and α_B as a function of Z as derived from our calibrations (solid lines). Dotted lines show the effects of the uncertainties affecting the luminosities of both star

have checked that without Debije-Huckel corrections and with the luminosities adopted by Edmonds et al. (1992), we find a Y-value (0.292), very close to theirs. Their convection parameters differ from ours but these differences are mostly due to their different low-T opacities and, to a lesser extent, to the different helium content of their calibrated models, to different effective temperatures and also possibly to another treatment of the photospheric layers and a different formulation of the MLT theory, on which we have no indication.

We have to point out that the techniques used in the calibrations do not affect the results. Actually, our calibration procedure with a unique α-value leads to Y=0.322 and Z=0.038, while with a fixed Z-value procedure, we obtain a very close solution, Y=0.318.

Lydon et al. (1993) also performed calibrations with fixed Z-values, MLT convection theory and Debe-Huckel correction in the equation of state. The derived X-values are in agreement since both groups used the interior opacities of Rogers & Iglesias (1992) and adopted the same observational luminosities. However, for the same effective temperatures, there are still differences in the values of the convection parameters, as can be seen from figure 1. These differences can be explained by the different low-T opacity tables and the different atmosphere treatment adopted in Lydon et al. (1993) calibrations.

2.1.4. Conclusions

The behaviour of α as a function of chemical composition could be a test of the unicity of α provided that, in the frame of the

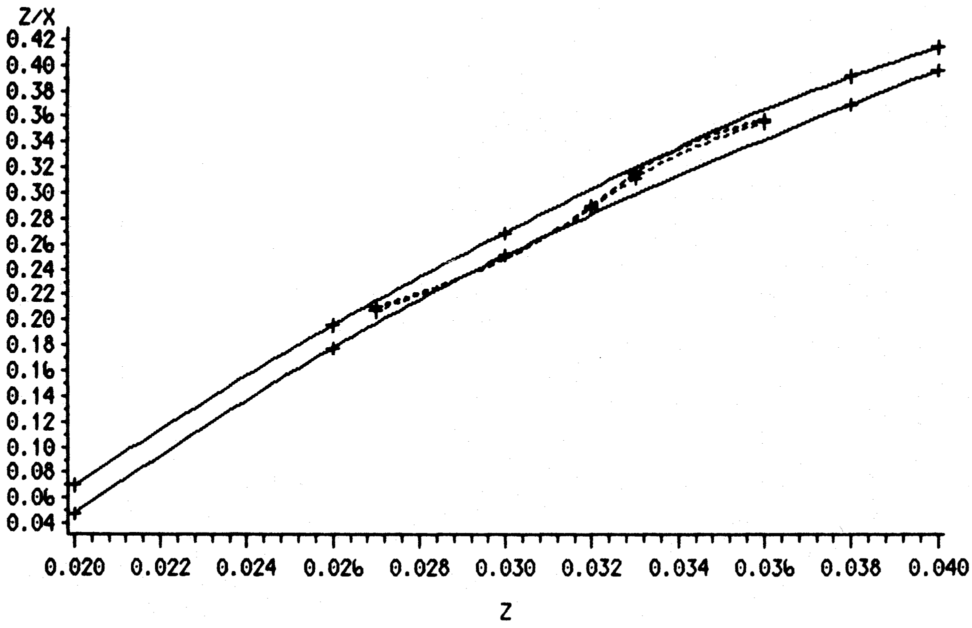

Fig. 4. $[\frac{Z}{X}]$ as function of Z, as derived from our MLT calibrations (solid line) and from the calibrations made with the convection treatment of Canuto & Mazzitelli (1991, 1992) (dotted lines)

same physics:
a)chemical composition, luminosities and effective temperatures are observationally sufficiently well constrained,
b)precise model atmospheres are used and low-temperature opacites are known with high accuracy.

2.2. Comparisons of our results with observational data

In Sect. 1, we mentioned that the observed value of $[\frac{Z}{X}]$ is in the interval 0.2 to 0.3. For our solutions given in Table 1, we calculated [Z/X] using $(\frac{Z}{X})_{\odot} = 0.0245$ (Grevesse & Noels 1993). Our results are presented in Table 2.

With 0.20 $\leq$ [Z/X] $\leq$ 0.30, we find 0.026 $\leq$ Z $\leq$ 0.033, our calibrated solution with a unique α-value even being outside that range. These possible solutions would, in principle, lead to different α-values for α Cen A and α Cen B. However, because of the uncertainties on the effective temperatures and luminosities, as shown in Figs. 2 and 3, we cannot exclude a unique α-value.

3. Calibrations using the treatment of convection of Canuto and Mazzitelli

Recently, Canuto & Mazitelli (1991, 1992) proposed a new treatment of convection, in which the parametrized mixing length $l = \alpha H_p$ is replaced by z, where z is the distance to the top of the convective envelope. In this frame, there is no free parameter in the convection theory and the effective temperatures can no more be adjusted at will.

We adopted the following technique for the calibration:
a) we fixed the metallicity;
b) for different values of the age of the system, t, we interpolated between two models of different Y, in order to determine the range of Y compatible with the observed luminosities and effective temperatures of both stars.

Table 2. [Z/X] calculated with solar data from Grevesse & Noels (1993)

Z	$[\frac{Z}{X}]$
0.020	[0.048, 0.070]
0.026	[0.178, 0.196]
0.030	[0.251, 0.269]
0.038	[0.370, 0.392]
0.040	[0.397, 0.415]

Table 3. Results obtained from our calibration using the convection theory of Canuto & Mazzitelli (1991, 1992). The values in brackets result from the uncertainties on the luminosities and on the effective temperatures

Z	Y	t(Gyr)	$[\frac{Z}{X}]$
0.027	[0.294,0.289]	[4.92,5.80]	[0.207,0.210]
0.0315	[0.307,0.310]	[4.85,5.50]	[0.289,0.290]
0.033	[0.311,0.317]	[4.45,5.40]	[0.312,0.316]
0.036	[0.316,0.320]	[4.45,4.90]	[0.356,0.358]

We applied that technique to Z=0.020, 0.024, 0.027, 0.0315, 0.033, 0.036 and 0.040. No solution could be found for $Z \leq$ 0.024 and $Z \geq$ 0.040.

Our results are presented in Table 3 with $[\frac{Z}{X}]$ calculated as in Sect. 2.2.

Figures 4 and 5 show a comparison between the $[\frac{Z}{X}]$- and t- values presented in Tables 1, 2 and 3. It can be seen that the solutions resulting from the convection treatment of Canuto & Mazzitelli (1991, 1992) are located in the envelope of our MLT solutions. Adopting the observational constraints on $[\frac{Z}{X}]$, we obtain Z-values similar to those presented in Sect. 2.2.

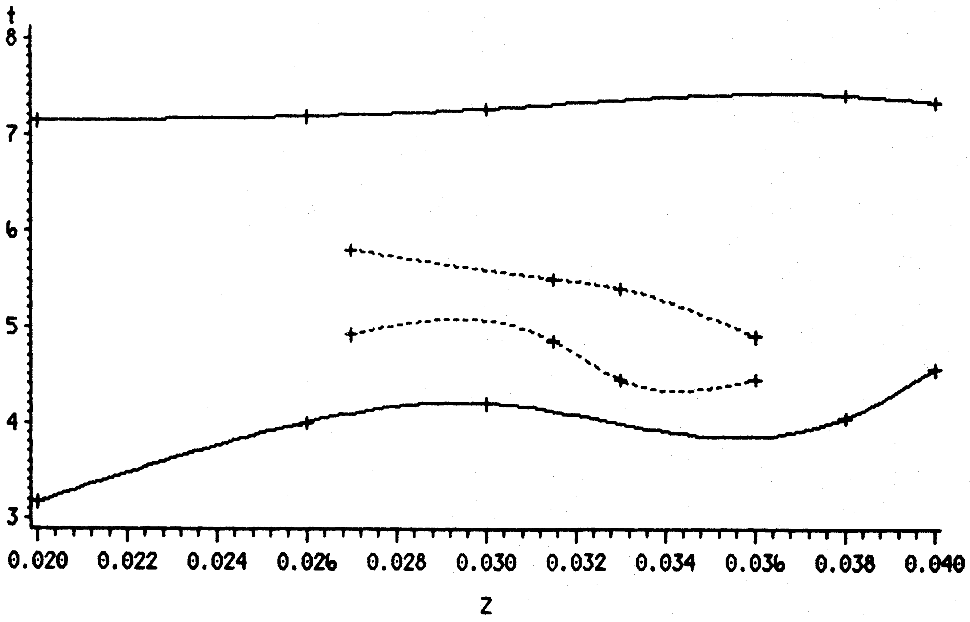

Fig. 5. t (in Gyr) as function of Z, as derived from our MLT calibrations (solid line) and from the "calibrations" made with the convection treatment of Canuto & Mazzitelli (1991, 1992) (dotted lines)

The uncertainties affecting the luminosities and effective temperatures of both components of the system imply that the metallicity cannot be constrained more tightly.

4. Conclusions

a) MLT

We can explain the high Z-value obtained in our calibrations with a unique convection parameter through the behaviour of α as a function of the chemical composition. Our calibrations with fixed Z-values are in agreement with those of Lydon et al. (1993) as far as Y is concerned. If the same effective temperature are adopted, the differences found in the convection parameters result essentially from different low-temperatures opacity tables in the calibrations.

The behaviour of α as a function of chemical composition could provide us with a test for the validity of the hypothesis of a unique convection parameter under the conditions that, in the frame of the same physics, an uncontroversial observational Z-value is derived, luminosities and effective temperatures are observationally well constrained, precise model atmosphere are used and low-T opacities are known with high accuracy.

b) Convection theory of Canuto and Mazzitelli

We have performed calibrations with models using the convection treatment of Canuto & Mazzitelli (1991, 1992) and we found acceptable solutions only for $0.024 \leq Z \leq 0.040$. This range becomes smaller, $0.026 \leq Z \leq 0.032$, if the observational domain of $[\frac{Z}{X}]$ is adopted, in agreement with the results obtained with the MLT theory.

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References

Bodenheimer P., Forbes J.E., Gould N.L., Henyey L.G., 1965, ApJ 141, 1019
Canuto V. M., Mazzitelli I., 1991, ApJ 370, 295
Canuto V. M., Mazzitelli I., 1992, ApJ 389, 724
Chmielewski Y., Friel E., Cayrel de Strobel G., Bentolila C. 1992, A&A 263, 219
Chmielewski Y., 1994, private communication
Cox J.P., Giuli R.T. 1968, Principles of Stellar Structure, Gordon and Breach Science Publishers, Inc., New York (eds)
Edmonds I., Lawrence C., Demarque P., Guenther D.B., Pinsonneault H.M., 1992, ApJ 394, 313
Huebner W. F., Mertz A. L., Magee Jr. N. H., Argo, M. F., 1977, Astrophysical Opacity Library, Los Alamos Scientific Lab., Report LA-6760-M
Edvardsson B., 1988, A&A 190, 148.
England M.N., 1980, MNRAS 191, 23.
French U.L., Powell A.T.L., 1971, Royal Obs. Bull. 173, 63.
Furenlid I., Meylan T., 1990, ApJ 350, 827.
Grevesse N., Noels A., 1993, Origin and Evolution of the Elements, Prantzos N., Vangioni-Flam E., Cass M. (eds), Cambridge University Press,p.14
Henyey L. G., Forbes J. E., Gould N. L., 1964, ApJ 139, 306
Henyey L. G., Vardya M. S., Bodenheimer P., 1965, ApJ 142, 841
Iglesias C.A., Rogers F.J., Wilson B.J., 1992, ApJ 397, 717
Krishna Swamy K. S., 1969, ApJ 145, 74
Lydon T.J., Fox P.A., Sofia S., 1993, ApJ 390, 413

Meylan T., Furenlid I., Meylan P., 1992 BAAS 23, 1384
Neuforge C., 1993a, A&A 268, 650
Neuforge C., 1993b, A&A 274, 818
Noels A., Scuflaire R., Gabriel M., 1984, A&A 130, 389
Noels A., Grevesse N., Magain P., Neuforge C., Baglin A., Lebreton Y., 1991, A&A 247, 91
Pagel B. E. J., 1994, private communication
Sackmann J., Boothroyd A. I., Fowler W. A., 1990, ApJ 360, 727
Wilson T. L., Rood R. T., 1994, ARA&A 32 (in press)

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