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Calibration of the α Centauri system: metallicity and age

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Abstract. The binary system α Cen A and B, with its well known parallaxe, its high quality orbit and the reasonable hypothesis of a common origin and age for both components is a useful test of stellar evolution models. We computed evolutionary sequences for $1.085\,M_\odot$ and $0.9\,M_\odot$ with different values of Z, Y and $\alpha\,(=l/Hp)$. Adopting luminosities and effective temperatures as derived from the observations, we find $Z=0.04$, $Y=0.32$, $\alpha=1.6$ and $t=5$ Gyr. We also show that the Z-value derived from evolutionary sequences is very sensitive to the difference in effective temperature between the two components.

Key words: Galaxy (the): solar neighbourhood – stars: abundances – evolution – HR diagram – α Cen

1. Introduction

The well known properties of the binary system α Centauri A and B make it an excellent candidate for testing theoretical stellar evolution sequences (see e.g. Flannery & Ayres 1978; Demarque et al. 1986). Its proximity to the sun allows high quality measurements of the parallaxe and of the orbital parameters and this in turn provides accurate values for the luminosities and the masses. Furthermore, the two components should have a common origin, which implies the same age and the same chemical composition.

Spectroscopic observations of those stars have revealed a problem in the determination of the metallicity. A first group of authors (French & Powell 1971; England 1980; Edvardsson 1988) found high metallicities, of the order of twice the solar value. On the other hand, Furenlid & Meylan (1990) very recently obtained a lower value, about 1.3 times the solar metallicity.

Flannery & Ayres (1978) computed evolutionary sequences, using Cox & Stewart (1969)'s opacities, and fitted their results to the observational data, assuming a given value of Z and choosing a value of the ratio of the mixing length to the pressure scale height ($\alpha=l/Hp$) in agreement with the value obtained for a standard solar model. As the age of the system, t, and its helium content, Y, are not known, this leaves two free parameters which can be adjusted from two observational constraints, namely both luminosities. The effective temperatures are not directly involved in the fitting. For $Z=0.02$, no satisfactory solution could be found: Y is below the primordial helium abundance. They could however find a solution for a high Z-value ($\sim 2\,Z_\odot$) leading to a Y-value of 0.246 and an age of 6.3 Gyr.

Demarque et al. (1986) adopted a similar procedure, also using Cox & Stewart (1969)'s opacities. However, they imposed fixed values for α and Y derived from their standard solar model, instead of using α and Z. As in Flannery & Ayres (1978), the T_e's play no role in the fitting technique. With their Y-value of 0.236, a solution is possible for a Z-value of 0.026 and an age of 4 Gyr, which agrees with the low Z-value, as shown by Furenlid & Meylan (1990).

Note that both Flannery & Ayres (1978) and Demarque et al. (1986)'s solutions lead to rather low Y-values ($Y\sim0.24$) as compared to the present Y-values ($Y\sim0.28$) obtained from standard solar models and also from observations. This comes from their use of Cox & Stewart (1969)'s opacities instead of the more recent Los Alamos opacities first distributed by Huebner et al. (1977), as shown by Guenther et al. (1989).

The apparent disagreement in Z between results derived from theoretical evolutionary sequences and also from spectroscopic observations have led us to reconsider the problem. However, in these double systems, the fitting between theoretical models and observations can be more complete. A calibration procedure analogous to the solar one can then be used. Its principle is very simple: the four observables (two luminosities and two effective temperatures) will determine the four unknowns of the modelisation of solar neighbours (helium content, metal content, age and mixing length parameter). With this new methodology and incorporating some new physical data, we have revisited the α Cen system. We have computed evolutionary sequences with the Los Alamos opacities (Huebner et al. 1977) and, assuming the same age and chemical composition for both stars, we determine the four free parameters Z, Y, t and α, from the observed values of the luminosities (L_A and L_B) and of the effective temperatures (T_{eA} and T_{eB}).

2. Input physics

The adopted masses for the A and B components are 1.085 and $0.9\,M_\odot$ respectively (Demarque et al. 1986). As these masses are very close to the solar one, the a priori hypothesis is that the same physical processes are acting in these three stars and in particular that the efficiency of convection is probably the same, i.e. the mixing length parameter should be the same as the solar one, using the same physical data.

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The nuclear reaction rates were taken from Fowler et al. (1975) and the opacities were derived from the Astrophysical Opacity Library (Huebner et al. 1977) with an estimation of the molecular opacities derived from Alexander (1975). The molecular opacities have been computed for $Z = 0.02$ and we were forced to use these data even for higher Z-values. This leads of course to an uncertainty in the external layers which is partly hidden in a value of the mixing length parameter, α, different from the solar one. The equation of state is the one given by Bodenheimer et al. (1965), improved by the introduction of electrostatic corrections and of better partition functions for H and He as described in Noels et al. (1984). Standard solar models (Noels et al. 1984; Lebreton & Maeder 1986) computed with similar data are in perfect agreement with the results of the other groups, as shown by Turck-Chièze et al. (1988). They predict a Y-value of about 0.28 while α ranges from 1.3 to 2.2, this spread in α being due to different choices of the molecular opacities in the outer layers (Sackman et al. 1991).

3. Observational data

Observations cannot give at present a definite value for Z. Values of $Z \sim 2\,Z_\odot$ have been found by French & Powell (1971), England (1980) and Edvardsson (1988) whereas Furenlid & Meylan (1990) obtained a lower Z-value ($\sim 1.3\,Z_\odot$). Because of these uncertainties, we have treated Z as a free parameter.

The observed luminosities have been derived from the magnitudes given by Ochsenbein et al. (1984), using a parallaxe of $0''.7506 \pm 0''.004$ (Demarque et al. 1986) and a bolometric correction of the order of -0.045 for α Cen A and -0.1545 for α Cen B. The effective temperatures given in the literature (Flannery & Ayres 1978; England 1980; Laird 1985; Soderblom 1986; Smith et al. 1986) show a rather good agreement for α Cen A while they display a larger dispersion for α Cen B. We adopted mean values: $T_{\rm eA} = 5765$ K and $T_{\rm eB} = 5290$ K. We discuss the implications of the uncertainties in both L's and $T_{\rm e}$'s in the last section.

Our observational L's and $T_{\rm e}$'s are:

α Cen A: $\log\frac{L}{L_\odot} = 0.1853 \qquad \log T_{\rm e} = 3.7608$

α Cen B: $\log\frac{L}{L_\odot} = -0.3065 \qquad \log T_{\rm e} = 3.7235$

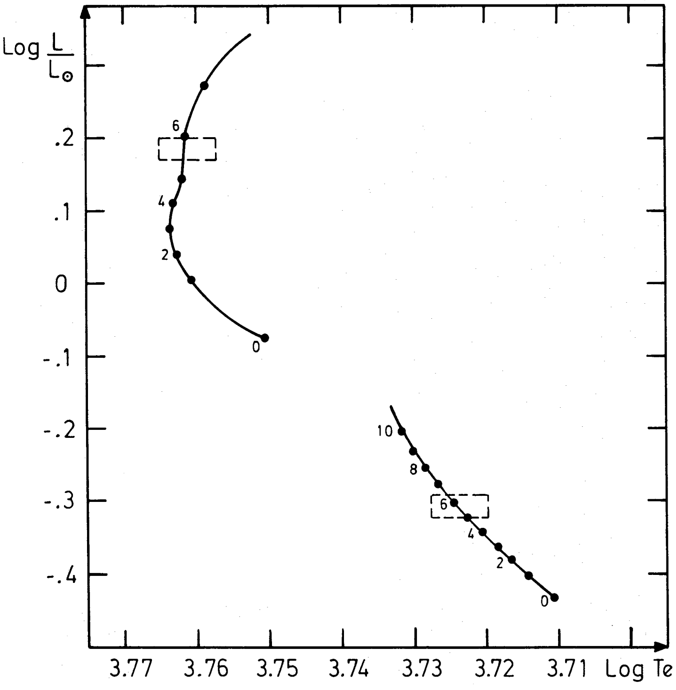

Fig. 1. Evolutionary tracks in the H-R diagram for our best fit $Y = 0.32$, $Z = 0.04$, $\alpha = 1.6$. The observational points for α Cen A and B are indicated together with their estimated uncertainties

4. Evolutionary models

The method employed here is a generalisation of the solar calibration technique. It consists of computing the partial derivatives of $\log L/L_\odot$ and $\log T_{\rm e}$ with respect to one of the free parameters Y, Z, α, t, keeping the three other parameters constant.

The solution is obtained by solving the following system of 4 equations in 4 unknows:

$$\left(\log\frac{L}{L_\odot}\right)_{\rm A,B} = \left(\log\frac{L}{L_\odot}\right)_{\rm Ref} + \left(\frac{\partial\log\frac{L}{L_\odot}}{\partial Y}\right)_{Z,\alpha,t}(Y - Y_{\rm Ref}) + \left(\frac{\partial\log\frac{L}{L_\odot}}{\partial Z}\right)_{Y,\alpha,t}(Z - Z_{\rm Ref}) + \left(\frac{\partial\log\frac{L}{L_\odot}}{\partial \alpha}\right)_{Y,Z,t}(\alpha - \alpha_{\rm Ref}) + \left(\frac{\partial\log\frac{L}{L_\odot}}{\partial t}\right)_{Y,Z,\alpha}(t - t_{\rm Ref}) \qquad (1)$$

$$(\log T_{\rm e})_{\rm A,B} = (\log T_{\rm e})_{\rm Ref} + \left(\frac{\partial\log T_{\rm e}}{\partial Y}\right)_{Z,\alpha,t}(Y - Y_{\rm Ref}) + \left(\frac{\partial\log T_{\rm e}}{\partial Z}\right)_{Y,\alpha,t}(Z - Z_{\rm Ref}) + \left(\frac{\partial\log T_{\rm e}}{\partial \alpha}\right)_{Y,Z,t}(\alpha - \alpha_{\rm Ref}) + \left(\frac{\partial\log T_{\rm e}}{\partial t}\right)_{Y,Z,\alpha}(t - t_{\rm Ref})$$

The subscript Ref refers to the values derived from one of the evolutionary tracks, taken as reference. The values of $\log L/L_\odot$'s and $\log T_{\rm e}$'s appearing in the left hand side of the equations are the observed values.

We have computed an extended set of evolutionary tracks for different values of Y, Z and α from the pre-main sequence contraction to the onset of hydrogen burning in a off-centre shell. The ranges of variations were as follows:

$0.20 < Y < 0.35$

$0.02 < Z < 0.04$

$1.6 \; < \alpha < 2.2\,.$

The free parameters have been adjusted in order to lead to H-R tracks located near the observational points, taking the error bars on L and $T_{\rm e}$ into account.

Using this procedure, we find:

$Z = 0.04 \qquad Y = 0.32$

$\alpha \;= 1.6 \qquad t \;= 5\,{\rm Gyr}\,.$

Figure 1 shows the evolutionary tracks computed with those parameters. One sees that the agreement with the observations is excellent for an age between 5 and 6 Gyr. The small discrepancy between the predicted age in our solution and the one given by the best fit in the evolutionary track results from the last term in the Eqs. (1). This term, at least one order of magnitude smaller than the others, leads to an uncertainty in t larger than in the other parameters.

5. Discussion

Our solution agrees with the spectroscopic observations showing a high Z-value, of the order of twice the solar metallicity.

We examine hereafter the influence of uncertainties in the luminosities and the effective temperatures on our solution.

5.1. Uncertainty in L

Adopting a conservative estimate for the observational uncertainty in L, of the order of $\Delta \log L/L_\odot \sim \pm 0.015$ dex, and keeping the effective temperature unchanged, we find ranges of change in our solution as follows:

$\Delta Z = \pm 0.003$	i.e.	$0.037 < Z < 0.043$
$\Delta Y = \pm 0.02$		$0.30 < Y < 0.34$
$\Delta\alpha = \pm 0.2$		$1.4 < \alpha < 1.8$
$\Delta t = \pm 0.5$		$4.5 < t < 5.5$

We see that *the observational uncertainties in the luminosities do not affect significantly our solution.*

5.2. Uncertainty in T_e

It is well known that the effective temperature depends on the quality of the photometries used to derive these data. More data exist for the brightest component α Cen A; they show a rather small dispersion, ± 50 K, around a mean value of 5765 K. Values for α Cen B are slightly more scattered around a mean value of 5290 K and are probably less accurate. We have adopted an uncertainty in T_e of 50 K for both components and we have examined the effects of this uncertainty on our solution, keeping the L's constant since we just showed hereabove that the uncertainties in L hardly affect our results. With this uncertainty in T_e, we shall successively move the observational points in the H-R diagram in the same horizontal direction and in opposite horizontal directions.

5.2.1. Constant ΔT_e

We first investigated the effect of a change in T_e's, keeping constant the effective temperature difference, $\Delta_{AB} = T_{eA} - T_{eB} = 475$ K. This corresponds to horizontal shifts of ± 50 K, i.e. nearly the same displacement in the H-R diagram for both stars. As it could be expected, a similar change in $\log T_e$ for both stars leads to the same solution with only an adjustment of α, of the order of ± 0.2. An increase in the mixing length parameter α shifts both evolutionary tracks to the leftward direction in the H-R diagram and vice versa.

5.2.2. Variable ΔT_e

We then examined the effects of opposite horizontal displacements in the H-R diagram leading to changes in the effective temperature difference, Δ_{AB}, of the order of twice the uncertainty in T_e, ± 100 K. Here, the situation is completely different. While rather slight relative changes in the solutions are obtained for α, t and Y, major variations occur for Z as can be seen hereafter:

$\Delta_{AB} = 575$ K
$\Delta Z = -0.022$, $\Delta Y = -0.06$, $\Delta\alpha = -0.2$, $\Delta t = -0.15$

$\Delta_{AB} = 375$ K
$\Delta Z = +0.016$, $\Delta Y = +0.03$, $\Delta\alpha = +0.2$, $\Delta t = 0.05$

This last solution leads to a Z-value of about 0.056 which is outside our domain of variations for Z and is therefore less accurate.

This shows the great importance of the effective temperature difference, Δ_{AB}, in fixing the metallicity. We therefore explored the solutions as obtained when varying Δ_{AB}, keeping T_{eA} constant ($=5765$ K). This constraint on T_{eA} is not very restrictive as we have shown in 5.2.1. Figure 2 shows X, Y, Z as functions of Δ_{AB}. In the whole range of variation of Δ_{AB}, we find α values of the order of 1.6 ± 0.5 and ages of about 5 ± 0.4 Gyr. We see that *the Z-value is extremely sensitive to the effective temperature difference between the two components*, with a dependence of about $\Delta Z/\Delta\Delta_{AB} \sim 0.01/50$ K. Our value of $Z \sim 0.04$ was obtained for $\Delta_{AB} = 475$ K i.e. $T_{eA} = 5765$ K and $T_{eB} = 5290$ K, in agreement with the high Z observations of about twice the solar metallicity (see Introduction). However, the low Z-value, 0.025, as obtained by Furenlid & Meylan (1990), would be found for $\Delta_{AB} = 550$ K i.e. $T_{eA} = 5765$ K and $T_{eB} = 5215$ K, still within the uncertainty limits.

The results reported in Fig. 2 should be accurate between $Z \sim 0.02$ and 0.04 and become less precise outside this range as no evolutionary tracks were computed for such extreme values of Z.

Note that our treatment of the molecular opacities could be improved; it might lead to slight modifications in the effective temperatures in the H-R tracks, although this effect is partly hidden in the mixing length parameter. New calculations are under way in order to explore the differential effects on the evolutionary tracks.

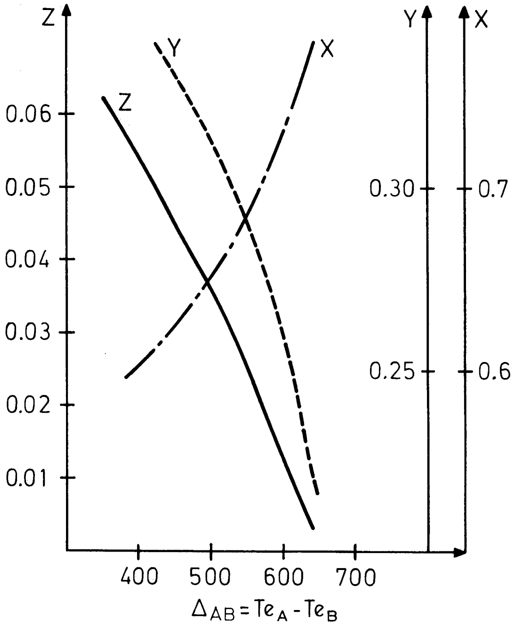

Fig. 2. Dependence of the chemical composition of the α Cen binary system versus the difference in effective temperature between the two components

6. Conclusions

We have shown that it is possible to obtain an excellent fit between the observational data for the binary system α Cen A and B and the theoretical evolutionary results for a metallicity of about twice the solar value, in agreement with one group of observations (French & Powell 1971; England 1980; Edvardsson 1988). However, this value has to be understood as a determination of the Z-value representing the stars, in the framework of the input data used here.

The helium content, $Y \sim 0.32$, is slightly larger than the solar value, $Y_{\odot} \sim 0.28$, the mixing length parameter α is equal to 1.6 and the age is about 5 to 6 Gyr. Our model leads to a galactic enrichment in helium and heavy elements of about $\Delta Y \sim 2\,\Delta Z$. This value is in agreement with the statistically derived value. However, the absence of an inverse correlation between the age and the metallicity reinforces the hypothesis of the existence of inhomogeneities in our Galaxy and suggests that this system has been formed far from the sun (Flannery & Ayres 1978) approximately at the same time.

We have also found that *the solution, and especially the metallicity, is extremely sensitive to the difference in effective temperatures,* Δ_{AB}, *between the two components.* A value of Δ_{AB} of about 550 K instead of our preferred value of 475 K, would lead to a Z-value of about 0.025, in agreement with the low Z observation of Furenlid & Meylan (1990). This value is still inside the uncertainty limits although, taking Furenlid & Meylan (1990)'s value for T_{eA}, 5710 K, we would obtain a value for $T_{eB} \sim 5160$ K, smaller than most of the observations.

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