A&A 427, 607–612 (2004)
DOI: 10.1051/0004-6361:20041141

Astronomy & Astrophysics

Detailed theoretical models for extra-solar planet-host stars

The "red stragglers" HD 37124 and HD 46375

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Received 22 April 2004 / Accepted 16 July 2004

Abstract. In this paper we analyse and discuss the HR Diagram position of two extra-solar planet-host stars – HD 37124 and HD 46375 – by means of theoretical stellar evolution models. This work was triggered by the results obtained by Laws et al. (2003) who found that these stars were in contradiction to the expectation based on their high metallicity.
Fixing the age of both stars with the value based on their chromospheric activity levels and computing our own evolutionary models using the CESAM code, we are able to reproduce the observed luminosity, effective temperature and metallicity of both stars for a set of stellar parameters that are astrophysically reliable even if it is non-trivial to interpret the absolute values for these parameters. Our results are discussed in the context of the stellar properties of low mass stars.

Key words. stars: individual: HD 37124 – stars: individual: HD 46375 – stars: evolution – stars: fundamental parameters – stars: Hertzsprung-Russel (HR) and C-M – planetary systems

1. Introduction

During the last few years a number of different detailed spectroscopic studies have revealed that planet-host stars are (on average) very metal-rich compared to field dwarfs (e.g. Gonzalez et al. 1997, 2001; Santos et al. 2000, 2001, 2004; Laws et al. 2003). Current results favour that this "excess" metallicity arises from the cloud of gas and dust that generated the star/planetary-system, suggesting that the formation of giant planets (at least the kind currently being discovered) is critically dependent on the grain content of the proto-planetary disk (e.g. Santos et al. 2004). This result has an enormous impact on theories of planetary formation.

In one of the studies mentioned above, Laws et al. (2003) analysed a sample of 30 F, G, K stars with companions (planets or brown dwarfs). They preformed spectroscopic observations in order to determinate their atmospheric parameters, including the effective temperature and metallicity. All the stars had accurate *HIPPARCOS* parallaxes, and thus the stellar position in the Hertzsprung-Russel Diagram (HRD) could be obtained precisely enough to derive stellar masses and ages from theoretical stellar models. To derive these parameters, Laws et al. (2003) used the evolutionary tracks from the Padova group (Salasnich et al. 2000). In their conclusions it is pointed out that for four stars in their sample (HD 6434, HD 37124, HD 46375, HD 168746) the derived ages were above 14.8 Gyr in spite of being Population I stars. They called this quartet the "red stragglers", because of their unexpected red position in the HRD.

The explanation for the position of these four stars in the HRD is not clear. Laws et al. (2003) suggested that it could be related to the presence of close-in low-mass stellar companions. However, to our knowledge none has been found by any Adaptative Optics survey. Laws et al. (2003) "recommend that these stars be the targets of detailed studies to determine the source(s) of their aberrant physical characteristics". We perform this study starting from a detailed analysis of the position of two of these objects in the HRD, to verify to what extent these two objects can be explained by current models of stellar evolution.

The knowledge of the HRD position of a star is dependent on many different variables. To first order, it is fixed by the stellar mass (M), the initial individual abundance of helium (Y) and metals (Z), and age ($t_\star$). The resolution of the equations of internal structure using the above parameters will give the values for the surface temperature and luminosity. However, the physical inputs chosen to describe the stellar interior also constrain the evolution of the star in the HRD. In particular, some mechanisms insufficiently known such as the convection, rotation and diffusion are dependent on free parameters. For instance, in the framework of the Mixing Length Theory (MLT, see below) currently used to model stellar convection, one more (unknown) variable has to be considered: the mixing-length parameter (α). So, to model a star correctly, we must determine the five parameters.

From the observational point of view, a detailed spectroscopic analysis of a single star may allows us to estimate its metallicity ([Fe/H] or Z/X, where $X = 1 - Y - Z$ is the abundance of hydrogen), its luminosity (L)[1] and its effective temperature, $T_{\rm eff}$. We are thus left with three known observables. In other words, we have an indeterminate problem: five unknowns to three observables. Gravity is also an issue in the spectroscopic analysis. So, a determination of the mass should, in principle, also be possible. However, a typical realistic error in $\log g$ is usually above 0.1 dex (e.g. Laws et al. 2003). This error implies an uncertainty on the derived solar mass stars of more than 0.15 $M_{\odot}$. Clearly, this error is too large to allow the gravity to be a real mass constraint.

This indeterminate problem can be solved for the Sun, for which the mass, metallicity and age are observationally known (Christensen-Dalsgaard 1982) and for some binary systems where individual masses are available (e.g. Noels et al. 1991; Fernandes et al. 1998). But for a single star (without a close-in stellar companion), other than the Sun, commonly there are more unknowns than observables, the situation that we have here.

In this work we analyze in detail two of the "red-stragglers" discussed by Laws et al. (2003), namely HD 37124 and HD 46375. Our goal is to find physically consistent models that are able to explain the position of these stars in the HRD. We have excluded HD 168746 and HD 6434 from this study: the former because it has no available chromospheric activity age (which would give us a further constraint – see below), and the latter because with a [Fe/H] $= -0.55 \pm 0.07$ it is on the frontier between Population I and Population II stars. In the modelling of Population II stars some effects become important. This is the case of the diffusion of chemical elements, NLTE corrections for the metallicity and α-elements contribution to the opacity (Lebreton et al. 1999). So, as the cumulated effects can be a supplementary source of errors, we prefer to exclude this case.

In Sect. 2 we present the stellar models and the theoretical description of our methodology used for modelling the stars. In Sect. 3 we compute models for HD 37124 and HD 46375. In Sect. 4 we present a discussion and conclusions in the context of the stellar proprieties of low mass stars. In particular, we show that the two stars studied in the current paper can be correctly modelled for some physically reliable values of the stellar parameters.

[1] Better determined if the distance to the star is known, as it is in our case.

2. Input physics in the theoretical stellar models and modelling method

We compute our models specially for the stars studied in this work. The stellar evolution calculations were done with the CESAM code version 3 (Morel 1997), running in the Coimbra Observatory, in Portugal.

Details on the physics of these models can be found in Lebreton et al. (1999): the CEFF equation of state, including Coulomb corrections to the pressure (Eggleton et al. 1973; Christensen-Dalsgaard 1991); nuclear reactions rates given by Caughlan & Fowler (1988); solar mixture from Grevesse & Noels (1993); OPAL opacities (Iglesias & Rogers 1996) complemented at low temperatures by opacity data from Alexander & Ferguson (1993) following a prescription of Houdek & Rogl (1996). The atmosphere is described with an Eddington $T(\tau)$-law; convection is treated according to the mixing-length theory from Bohm-Vitense (1958) leaving the mixing-length ($\alpha \times H_p$) unknown, and thus α as a free parameter, where H_p is the pressure scale height. With these input physics the solar model fits the observed luminosity and radius, with a relative precision of 10^{-3}, with $\alpha = 1.63$, helium abundance $Y = 0.268$ and $Z = 0.0175$ for the common accepted solar age of 4.6 Gyr (Dziembowski et al. 1999) and the ratio of the solar mixture from Grevesse & Noels (1993). This model does not take into account microscopic diffusion of helium or metals.

There are other mechanisms, not included in this work, that could affect the HRD position of a model, such as the rotation (Maeder & Meynet 2000), overshooting of the convective core, or helium and metal gravitational settling (microscopic diffusion). However, the stars is this work are slow rotators (as are all planet-hosts, since it is more difficult to obtain accurate radial-velocities for fast rotating stars) and solar mass stars do not develop permanent convective cores (Ribas et al. 2000). On the other hand, diffusion has a marginal effect on the HRD position for Population I solar mass stars. Lastennet et al. (2003) have shown that for a 0.98 $M_{\odot}$ star with $Z = 0.012$, the inclusion of helium and metal diffusion may change the $T_{\rm eff}$ of the evolutionary track by no more than 65 K, even for an old age of 10 Gyr. For Population I stars, the density in external layers is sufficiently high to break the diffusion efficiency. We thus expect that the lack of these mechanisms do not considerably change our results.

As discussed above, modelling a single star, for a fixed age, is reduced to the problem of finding the solutions of the four stellar parameters M, Y, Z and α, that adjust the three observational parameters L, $T_{\rm eff}$, and Z/X.

Inspired by solar modelling (Christensen-Dalsgaard 1982), we construct the following system composed of the three equations:

$$\left(\log \frac{L}{L_{\odot}}\right)_{\rm obs} = \left(\log \frac{L}{L_{\odot}}\right)_{\rm ref} + \sum_i^4 \left(\frac{\partial \log \frac{L}{L_{\odot}}}{\partial X_i}\right)_{j\neq i} \times (X_i - X_{i_{\rm ref}}) \quad (1)$$

$$\log T_{\rm eff_{obs}} = \log T_{\rm eff_{ref}} + \sum_i^4 \left(\frac{\partial \log T_{\rm eff}}{\partial X_i}\right)_{j\neq i} \times (X_i - X_{i_{\rm ref}}) \quad (2)$$

$$\left(\frac{Z}{X}\right)_{\rm obs} = \frac{Z}{1 - Y - Z} \quad (3)$$

where X_i with $i = 1, 2, 3$, and 4 are M, Y, Z, α, respectively. The subscript "ref" indicates the reference stellar evolutionary model that falls inside the observational error bars. We consider as a satisfactory solution the sample (M, Y, Z, α), obtained by solving the above system assuming the linearity of the variation of the $\log L/L_\odot$ and $\log\ T_{\rm eff}$ with mass, helium, metals and α for a fixed value of the age. Theoretically, each solution of the system should fit exactly the observed luminosity and effective temperature, for the fixed age. In practice, thanks to our linear approximation, in some rare situations the solution is outside the error bars. However, in these situations the solution is still near and a small change in one parameter is enough to put the evolutionary track in the error bar. On the other hand, as we have more unknowns than equations, the above system has an infinite number of solutions. In this work we chose to present five solutions for each star in order to illustrate the range of variation of the stellar parameters (M, Y, Z, α).

3. Modelling HD 37124 and HD 46375

In the following we will use the ages for HD 37124 and HD 46375 that have been estimated by Laws et al. (2003) using a chromospheric activity-age calibration from Donahue (1993). The knowledge of this age gives us the possibility to limit the number of models available. We have thus fixed the age for each star (3.9 and for 4.5 Gyr for HD 37124 and HD 46375, respectively) and estimated the other four unknown parameters (M, Y, Z, α) by theoretical stellar evolutionary models, taking into account the three observables (L, $T_{\rm eff}$, Z/X). So, opposite to Laws et al. (2003), we have chosen not to fix the values of α and $\frac{\Delta Y}{\Delta Z}$ in our models. We note that our major goal is to find an astrophysically reliable solution for the position of these stars in the HRD, i.e. a solution that matches the observable quantities. We thus prefer to be as strict as possible in our observable constraints. Leaving the age as a free parameter would, of course, make this solution easier to obtain, but this solution would probably not be reliable.

3.1. HD 37124

3.1.1. HD 37124: Observations

HD 37124 is a G4 IV–V star ($V = 7.68$; $B - V = 0.667$) in the solar neighbourhood at a distance of 33.2 pc (*HIPPARCOS* – Perryman et al. 1997). Vogt et al. (2000) reported the discovery of a candidate planet around this star, followed by the discovery of a second planetary-mass companion in the system (Butler et al. 2003). Since then, particular attention has been paid to this object, e.g., detailed spectroscopic analyses (Laws et al. 2003; Santos et al. 2004) or studies of the dynamical stability of the discovered planetary system (Zhou & Sun 2003).

In the following we will consider the spectroscopic determinations and magnitudes given by Laws et al. (2003): $T_{\rm eff} = 5551 \pm 34$ K; [Fe/H] $= -0.37 \pm 0.03$ and $M_V = 5.07 \pm 0.08$. These spectroscopic results are in excellent agreement with the recent values obtained by Santos et al. (2004): $T_{\rm eff} = 5546 \pm 30$ K; [Fe/H] $= -0.38 \pm 0.04$.

Table 1. Observations of HD 37124 and HD 46375 (see text for details).

Star	$L/L_\odot$	$T_{\rm eff}$ (K)	Z/X
HD 37124	0.84 ± 0.06	5551 ± 34	0.0105 ± 0.0008
HD 46375	0.74 ± 0.06	5241 ± 44	0.049 ± 0.004

Table 2. Models of HR 37124 for an age of 3.9 Gyr. M is the mass of the model (in $M_\odot$), Y is the initial helium abundance, Z is the initial metal abundance, α the mixing length (in units of the local pressure scale height).

Model	M	Y	Z	α	$T_{\rm eff}$ (K)	$L/L_\odot$
model 1	0.86	0.29	0.0074	0.85	5548	0.84
model 2	0.90	0.27	0.0076	0.90	5526	0.84
model 3	0.92	0.25	0.0079	0.95	5535	0.84
model 4	0.94	0.24	0.0079	1.00	5542	0.84
model 5	0.90	0.27	0.0076	1.10	5668	0.84

For Population I stars, the abundance of metals Z is related to the [Fe/H] by [Fe/H] $= \log(Z/X) - \log(Z/X)_\odot$, where $(Z/X)_\odot = 0.0245$ is the ratio of the solar mixture (Grevesse & Noels 1993). This implies $(Z/X) = 0.0105 \pm 0.0008$ for HD 37124.

Using the $T_{\rm eff}$ of Laws et al. (2003) we derive a bolometric correction from Flower (1996) of $BC = -0.13 \pm 0.01$. This implies a bolometric magnitude of $M_{\rm bol} = 4.94 \pm 0.08$. Assuming that the bolometric magnitude of the Sun is 4.75 (e.g. Cayrel 2002), we obtain a luminosity of 0.84 ± 0.06 times the solar luminosity ($L_\odot$) for HD 37124. From the Stefan-Boltzmann law we can thus estimate the radius of this star: $0.99 \pm 0.05\,R_\odot$. This result is in very good agreement with the infrared photometry determination of 1.004 ± 0.039 from Ribas et al. (2003). The observable stellar parameters used to constraint the models are summarised in Table 1.

3.1.2. HD 37124: Models

We have computed several models for HD 37124, fixing the age at 3.9 Gyr from Laws et al. (2003), in the following range of parameters: 4 values of mass in [0.75, 0.95], 4 values of helium in [0.24, 0.30], 4 values of metallicity in [0.00669, 0.01000] and 5 values of α in [0.8, 1.6]. This sample of models allows us to obtain the derivatives of L and $T_{\rm eff}$ in relation to (M, Y, Z, α) in the system of Eqs. (1)–(3). Using the observed values (L, $T_{\rm eff}$, Z/X) we can then establish a linear system for the reference model with the following characteristics: $M = 0.94\ M_\odot$, $Y = 0.24$, $Z = 0.0079$, and $\alpha = 1.00$. This model reproduces the observed quantities (L, $T_{\rm eff}$, Z/X), within the errors, for an age of 3.9 Gyr.

In Table 2 we present the models from 1 to 4 that reproduce the observations within the error bars and in Fig. 1 we provide the corresponding evolutionary tracks in the HRD from the ZAMS to 3.9 Gyr. The number of possible models that fall inside the observed error bars is infinite. The first four models were chosen in order to show the dependence of the solution

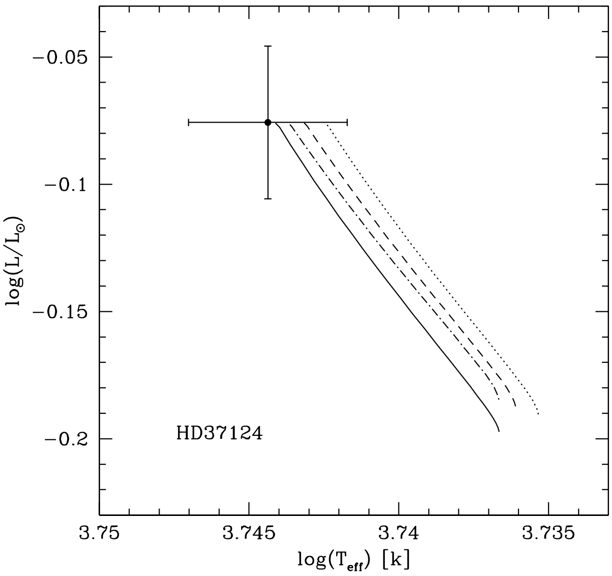

Fig. 1. Evolutionary tracks for HD 37124. The different lines represent models 1 (solid line), 2 (dotted line), 3 (dashed line), and 4 (dot-dashed line). See text for more details.

on M, Y, Z and α. Model 5 is computed taking into account an increase in the observed $T_{\rm eff}$ of about 3σ (see Discussion and conclusions). The correponding luminosity is 0.82 $L_{\odot}$, still inside the original error bar.

The five solutions have in common low values of the mixing-length parameter, α. This is probably the reason why Laws et al. (2003) did not find a satisfactory solution in their analysis[2]. In fact, all the Padova isochrones are built using the solar α value (∼1.7), the same for all stellar models. This approximation, currently made on the isochrone computations for simplicity, is not clear: why should stars with different masses, chemical composition and evolutionary status, have the same α? Some recent results on stellar systems conclude that there are variations of α with mass (Lebreton et al. 2002), including values of α lower than 1.0 (Lastennet et al. 2003). On the other hand, the helium and mass are values expected for this star.

3.2. HD 46375

3.2.1. HD 46375: Observations

HD 46475 is a K1 IV–V star ($V = 7.91$; $B - V = 0.860$), lying in the solar neighbourhood: $d = 33.4$ pc (Perryman 1997). This star was recently found to be orbited by a possible planetary-mass companion (Marcy et al. 2000).

To build the observed HRD we consider here the parameters derived by Laws et al. (2003): $T_{\rm eff} = 5241 \pm 44$ K; [Fe/H] = +0.30 ± 0.03 and $M_V = 5.29 \pm 0.08$. These spectroscopic results are in good agreement with the recent results by Santos et al. (2004) for the effective temperature ($T_{\rm eff} = 5268 \pm 55$ K) and are in fair agreement with the metallicity ([Fe/H] = +0.20 ± 0.06). Computed as described above, the metal abundance of this star is $(Z/X) = 0.049 \pm 0.004$.

[2] By "satisfactory solution" we mean the one that, for a fixed age, reproduces the observational constraints (L, $T_{\rm eff}$, Z/X).

Table 3. Models of HD 46375, for an age of 4.5 Gyr. M is the mass of the model (in $M_{\odot}$), Y is the initial helium abundance, Z is the initial metal abundance, α the mixing length (in units of the local pressure scale height).

Model	M	Y	Z	α	$T_{\rm eff}$ (K)	$L/L_{\odot}$
model 6	0.96	0.31	0.032	1.15	5236	0.71
model 7	0.98	0.31	0.032	1.05	5224	0.79
model 8	1.01	0.29	0.033	1.10	5200	0.77
model 9	1.03	0.27	0.034	1.35	5272	0.71
model 10	1.03	0.27	0.034	1.55	5369	0.72

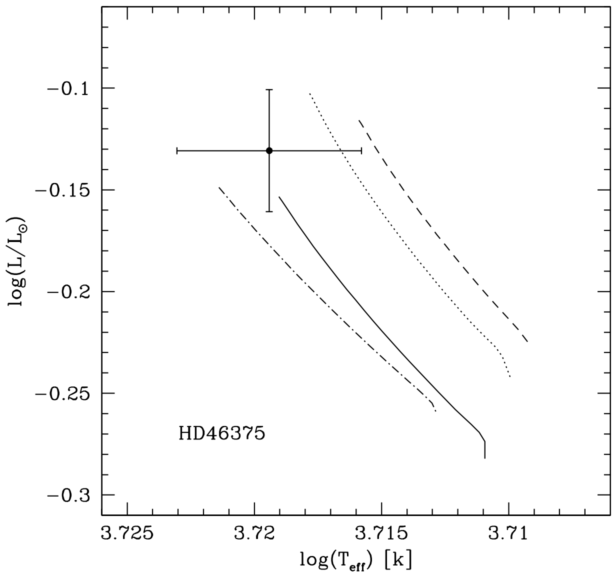

Fig. 2. Evolutionary tracks for HD 46375. The different lines represent models 6 (solid line), 7 (dotted line), 8 (dashed line), and 9 (dot-dashed line). See text for more details.

Using the $T_{\rm eff}$ of Laws et al. (2003) we can derive the bolometric correction of $BC = -0.21 \pm 0.03$ (Flower 1996), a value that implies a bolometric magnitude $M_{\rm bol} = 5.08 \pm 0.09$, and a luminosity of 0.74 ± 0.06 $L_{\odot}$; the corresponding stellar radius is 1.05 ± 0.06 $R_{\odot}$, once more in very good agreement with Ribas et al. (2003): 1.005 ± 0.036 $R_{\odot}$. The observations chosen to constrain the models are provided in Table 1.

3.2.2. HD 46375: Models

As done for HD 37124, we computed several models for HD 46375, fixing the age at 4.5 Gyr from Laws et al. (2003) in the following range of stellar parameters: 4 values of mass in [0.95, 1.05], 4 values of helium in [0.24, 0.30], 4 values of metals in [0.025, 0.035] and 4 values of α in [0.8, 1.6].

The reference model has the following chacteristics: $M = 1.00$ $M_{\odot}$, $Y = 0.30$, $Z = 0.036$ and $\alpha = 1.0$. This model is sufficiently near the observed quantities (L, $T_{\rm eff}$, Z/X) for an age of 4.5 Gyr.

In Table 3 we present four derived models, from 6 to 9, that reproduce the observations within the error bars and in Fig. 2 we plot the correspondent evolutionary tracks in the HRD from the ZAMS to 4.5 Gyr. As for the previous star we chose four models to give the range of variation of each parameter M, Y, Z and α. Model 10 is computed taking into account an increase of 3σ in the observed $T_{\rm eff}$. As previously, the corresponding luminosity is 0.71 $L_{\odot}$, falling inside the original error bars.

As for HD 37124, the models from 6 to 9 present low α values confirming that a probable explanation for the difficulty of Laws et al. (2003) in finding a solution with a "reliable" age can be attributed to the constant value of α in the Padova models.

4. Discussion and conclusions

In this paper we present detailed evolutionary models that reproduce the observed HRD position and metallicity of the planet-host stars HD 37124 and HD 46375. In order to reduce the high degeneracy degree of modelling a single star we fixed the stellar age given by the age-cromospheric activity relation.

The main goal of this paper is to show that it is possible to model these stars using astrophysically reliable values of mass, helium and metal abundances, and mixing length parameters. We found that this is indeed the case, although α and $\frac{\Delta Y}{\Delta Z}$ values are not considered as a constants from one model to another. The hypothesis of constant values is current in published isochrones. We propose that the "aberrant" solutions found by Laws et al. (2003) for HD 37124 and HD 46375 are caused by the assumption of the above hypothesis, particularly the one about the mixing length parameter.

Eventual differences between the internal structure of the CESAM and Padova evolutionary codes, as well as between our modelling method and the one used by Laws et al. (2003), can't explain our results. The three following reasons support this: first, the input physics, namely the radiative opacities, equation of state and convection formalism, are similar in the two codes; second, we confirm the difficulty of Laws et al. (2003) in modeling the above stars using solar values for α and $\frac{\Delta Y}{\Delta Z}$; and third, we tested our modelling method in HD 117176, one star also studied by Laws et al. (2003), and for which they have found a satisfactory solution. Using the mass derived by these authors, as well as the same α and $\frac{\Delta Y}{\Delta Z}$ used in the Padova isochrones, we find a solution in the HRD for an age of 8.8 Gyr, close to the 7.9 Gyr derived by them.

Among an infinite number of combinations of stellar parameters (M, Y, Z, α) that, for a fixed age, reproduce the observables (L, $T_{\rm eff}$, Z/X)[3] we have computed four models for each star, inside an acceptable range of variation for each parameter. As we do not have complementary observational constraints we cannot choose the best model(s). However, some astrophysical arguments, such as the reliable values of the helium-to-metals chemical enrichment parameter $\frac{\Delta Y}{\Delta Z}$ (e.g. Jimenez et al. 2003) could allow us to constrain the solutions. Note that our solutions are age dependent.

Understanding why these stars are well modelled using a low α value, while that is not the case for other stars in the sample of Laws, is beyond the scope of this paper. The MLT is a local, 1D and non-compressive theory to explain a non-local, 3D and highly compressible system, as is stellar convection. Many works and authors (e.g. Canuto & Mazzitelli 1991; Ludwig et al. 1999), have already shown the limitations of this formalism. However MLT is easy to implement in stellar evolutionary codes and is a relatively successful in reproducing global observations of the Sun and stellar systems. The low values of α found in this work probably reflect the limitations on the MLT itself more than a real physical effect. The analysis of these stars using alternative convective description such as the formalism of Canuto & Mazzitelli (1991) could give important constraints on the super-adiabatic layer in the convective region, where convective efficiency is strongly dependent on α. However, we cannot exclude that the derived low values for α are due to some other unknown effect.

It is well known that the $T_{\rm eff}$ of low mass stellar models depends on α, thanks to its influence in the super-adiabatic layer and, thus, on stellar radius. Are there erroneous $T_{\rm eff}$ determinations? We have checked that if the observed $T_{\rm eff}$ is increased by 3σ for each star, we can find a solution with a high α value for both stars (models 5 and 10). In particular, model 10 has an α value closer to solar. On the other hand these changes in $T_{\rm eff}$ must be weighted by the fact that systematic differences between various observational temperature scales are never above 100–200 K (cf. Laws et al. 2003; Santos et al. 2004). So at least for HD 46375 the reason for the "aberrant solution" found by Laws et al. (2003) may be an underestimation of $T_{\rm eff}$.

The solutions found for each star are all in a range lower than 0.1 solar masses. This can be particularly important for the estimation of the mass the planets harboring stars, and that could have a strong impact e.g. on the study of the relation between the stellar mass and the frequency of giant planets (Santos et al. 2003; Laws et al. 2003). Furthermore, the wrong masses derived from the standard evolutionary models (with, among other things, α fixed to the solar value) may imply incorrect derivations of the surface gravities using Hipparcos parallaxes (e.g. Nissen et al. 1997). If the values of α depend e.g. on the effective temperature of the star, this problem may induce a systematic error in the gravities with temperature when comparing spectroscopic and parallax-based $\log g$ values, an effect that was mentioned in Santos et al. (2004).

If indeed parameters like α vary from star to star, the determination of accurate ages by means of isochrone fitting may introduce important systematic errors. This was the case for the two stars studied in this paper, but may be the case for many other objects thus, specific stellar models must be computed for individual objects.

Acknowledgements. We would like to thank the referee, Dr. Achim Weiss, for his helpful suggestions to improve the manuscrit. This work was supported in part by Fundação para a Ciência e a Tecnologia – Portugal, through POCTI-SFA-2-675. JF gratefully thank David Valls-Gabaud who installed the CESAM code at the Coimbra Observatory. This work was done with the help of the CDS-Strasbourg Data Base. Support from Fundação para a Ciência e Tecnologia (Portugal) to N.C.S. in the form of a scholarship is gratefully acknowledged.

[3] As mentioned above, the modelling of a single star other than the Sun is an indeterminate problem, given that there are more unknowns than observables.

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