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Convection Treatment in Solar Type Stars

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Abstract: The convection theory proposed by Canuto & Mazzitelli (1991) is a new approach in the treatment of convection in stellar convective envelopes. An important aspect is that it takes a large range of convective eddies into account, instead of the "mean" eddy adopted in the mixing length theory of Böhm-Vitense, MLT.

A calibration of the Sun with this theory leads to a solution which is very close to the MLT solution. We apply this theory to the calibration of the α Centauri system. Our results lead to constraints on the metallicity of the system similar to those obtained with MLT.

1 Introduction

The treatment of convection is one of the most interesting and difficult problems to be solved in stellar astrophysics. The mixing length theory (MLT) has been proposed a hundred years ago and has given satisfactory results when describing engineering flows. The MLT has then been applied to the stellar turbulent convection by Böhm-Vitense in 1958. The simple form of this formalim arises from the following assumptions (Cox & Giuli, 1968): the actual convective elements, or eddies, are replaced by a group of "average" convective elements having the same physical properties and the same average speed at a given radial distance from the center, travelling a distance Λ, the mixing length, before mixing with the surroundings, and having the same characteristic dimension, equal to Λ, in all directions.
The MLT is a local theory and cannot provide the value of Λ, which is currently written as $\Lambda = \alpha Hp$, where Hp is the pressure scale heigth and α, an adjustable parameter.

With an adequate tuning of α, a theoretical model can reproduce the observed effective temperature of a star with a convective envelope as well as some other observational properties of that star. The extreme simplicity of the MLT formalism and the lack of other implementable descriptions of the stellar convection explain that the MLT has widely been used.

Unfortunately, the MLT contains a main inconsistency. Canuto & Mazzitelli (1991) have shown that a "one eddy" model is not a good approximation of the real eddy spectrum in a nearly inviscid medium such as a stellar interior. Furthermore, the use of a convection parameter helps in hiding the uncertainties affecting the convection treatment but also those affecting the

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"input physics", that is the low temperature opacities, the atmosphere treatment, the equation of state, ...

To avoid the problems raised by the MLT, new attempts have recently been made to derive a more physical model of convection. Chan & Sofia (1989) performed numerical simulations of compressible turbulent convection and their results have been included in the YALE evolutionary code (Lydon et al., 1993).

Canuto & Mazzitelli (1991) derived a turbulent convection model which takes a large spectrum of eddies into account. In this convection treatment, the hydrodynamical equations are written in the frame of the Boussinesq approximation. Thus, the theory is local and cannot be applied to the whole convective envelope, in which the Rayleigh number varies by orders of magnitude, unless a characteristic length is used. Canuto & Mazzitelli take this length to be equal to the distance from a given point to the top of the convection zone, z. Then, the convective flux can formally be written similarly to its MLT expression.

2 Stellar calibrations

2.1 The Sun

A calibration of the Sun, using $\frac{Z}{X} = 0.0245$ (Grevesse & Noels, 1993), OPAL interior opacities (Iglesias et al., 1992) and Neuforge (1993) low temperature opacites leads to

$$Y_\odot = 0.263 \quad Z_\odot = 0.017$$

which is very close to our MLT result:

$$Y_\odot = 0.266 \quad Z_\odot = 0.018 \quad \alpha_\odot = 2.06$$

2.2 α Centauri

2.2.1 Observational data

Alpha Centauri is the closest binary system. The masses and the luminosities of its two components, α Cen A and B , both solar-like stars, can thus be determined with a good accuracy. Spectroscopic analyses provide the effective temperatures of both stars and the metallicity of the system, but this last quantity is still controversial. The most recent values of the observational data are the following ones:

$M_A = 1.085\ M_\odot$	$M_B = 0.900 M_\odot$	see Noels et al. (1991)
$Log(\frac{L}{L_\odot})_A = 0.1853 \pm 0.015$	$Log(\frac{L}{L_\odot})_B = -0.3065 \pm 0.015$	
$Te_A = 5800 \pm 20K$	$Te_B = 5325 \pm 50K$	Chmielewsky et al. (1992)
$log(\frac{Z}{Z_\odot}) = +0.20$		Meylan et al. (1992)
$[\frac{Fe}{H}]_{\alpha CenA} = +0.22 \pm 0.02$		Chmielewsky et al. (1992)
$[\frac{Fe}{H}]_{\alpha CenB} = +0.26 \pm 0.04$		Chmielewsky et al. (1992)

2.2.2 Results

The two stars can reasonably be assumed to have the same age and the same chemical composition but we have no indication on their age, t, and on their helium content, Y. These quantities can nevertheless be derived through a calibration of the system.

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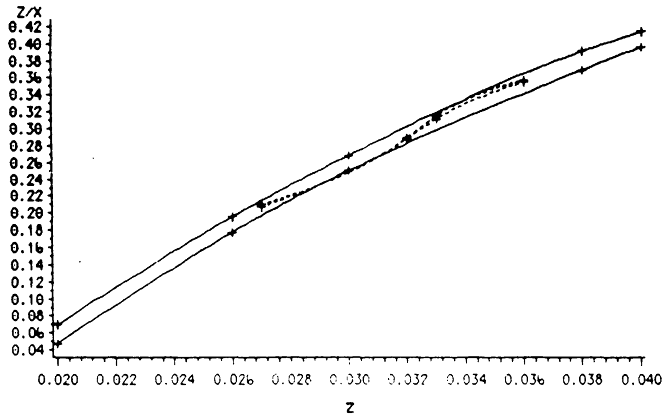

Figure 1: $[\frac{Z}{X}]$ as function of Z, as derived from our MLT calibrations (solid line) and from the calibrations made with the convection treatment of Canuto & Mazzitelli (1991) (dashed lines). $[\frac{Z}{X}]$ has been calculated with $(\frac{Z}{X})_\odot = 0.0245$ (Grevesse & Noels, 1993).

In a calibration in the MLT frame, the convection parameter is also unknown. Two different calibration methods have been proposed. The first, developed in YALE (Edmonds et al., 1992, Lydon et al., 1993), is performed for fixed Z-values and a different convection parameter for each star. The second, developed in Meudon and Liège (Noels et al., 1991) makes the hypothesis of a unique α for both stars and considers Z as an unknown.

Nevertheless, even in the Alpha Centauri system, in which both components are solar like, the unicity of this parameter may be questionable (Fernandes & Neuforge, 1995).

We have performed calibrations with fixed Z-values (Fernandes & Neuforge , 1995) and find results consistent with those of Lydon et al. (1993), as far as the chemical composition is concerned, while our convection parameters differ from theirs. The differences can however be explained by the different effective temperatures and low temperature opacities used in the calibrations (Fernandes & Neuforge, 1995). Unfortunately, observational data and input physics suffer from uncertainties which implie that the possible unicity of α cannot be tested yet.

Then, we used the convection theory of Canuto & Mazzitelli (1991), with $\Lambda = z$, to calibrate the α Cen system. These calibrations were also performed for different fixed Z-values, and contrary to the MLT, they don't provide solutions for any Z-value, but only for $0.024 \leq Z \leq 0.040$. Figure 1 shows a comparison between the results of fixed Z calibrations performed in the MLT frame and with the convection treatment of Canuto & Mazzitelli (1991). This new treatment leads to solutions located in the envelope of the MLT solutions.

A comparison between the observed and calibrated $[\frac{Z}{X}]$ leads to the same constraint on Z in both types of calibration: $0.026 \leq Z \leq 0.033$.

2.2.3 Internal structure of the models

We considered two calibrated models of α Cen A and B, calculated with the convection treatment of Canuto & Mazzitelli (1991). In order to compare the changes induced by this new convection treatment on the internal structure, we calculated MLT models having the same chemical composition, effective temperatures and luminosities. The main characteristics of the models are presented in table 1. As already pointed out by Canuto & Mazzitelli (1991), the physical conditions in the central layers and at the basis of the convection zone, as well as the thickness of this zone are not significantly affected by the convection treatment, which induces

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X	Y	Z
0.660	0.308	0.032

	α Cen A					α Cen B					
	α	t(Gyr)	Mbol	Te(K)			α	t(Gyr)	Mbol	Te(K)	
MLT	1.956	5.148	4.316	5808		MLT	1.900	5.123	5.522	5295	
C & M	—	5.142	4.316	5809		C & M	—	5.142	5.522	5295	
	$T_c(K)$	ρ_c	X_c	M_{be}	T_{be}		$T_c(K)$	ρ_c	X_c	M_{be}	T_{be}
MLT	1.881e7	2.632e2	0.01290	0.9871	1.801e6	MLT	1.392e7	1.182e2	0.425	0.9489	2.800e6
C & M	1.876e7	2.646e2	0.01230	0.9873	1.791e6	C & M	1.392e7	1.184e2	0.424	0.9493	2.793e6

Table 1: Characteristics of calibrated models of α Cen A and B, calculated with the convection treatment of Canuto & Mazzitelli (1991) and with MLT, for the same chemical composition, effective temperatures and luminosities. $T_c(K)$, ρ_c and X_c are the temperature, density and hydrogen abundance at the center, while M_{be} and T_{be} are the mass fraction and the temperature of the basis of the convective envelope.

changes only in a thin layer located near the surface.

We considered each star separately. Nevertheless, the following comparison is valid for both stars. The models have different temperature gradients, $\nabla \equiv \frac{dlnT}{dlnP}$, and thus different temperature distributions in the highest part of their convective envelope. In this region of a model calculated with the convection treatment of Canuto & Mazzitelli (1991), z is smaller than $\Lambda = \alpha Hp$. The efficiency of convection, which is proportional to Λ^2 is thus lower. As a result, the convection is more overadiabatic (Cox & Giuli, 1968) than in the MLT case and ∇ shows thus a higher peak, as can be seen from fig. 2. Deeper in the convection zone, z becomes greater than αHp and the temperature gradient sticks to the adiabatic one closer to the surface than in the MLT case.

3 Conclusions

Canuto & Mazzitelli (1991) proposed a new theory to treat convection in stellar envelopes. Although this theory is derived from a turbulent convection model and takes a large range of convective eddies into account, it remains local and needs the prescription of a characteristic length to be applied to the whole convective envelope.

We calibrated the Sun and α Centauri system with two different treatments of convection: the mixing length theory of Böhm-Vitense (1958) and the new convection treatment of Canuto & Mazzitelli (1991). This new convection treatment leads, for the Sun, to a solution which is very close to the MLT solution and, for α Cen, to solutions located in the envelope of the MLT solutions.

We compared models of α Cen A and B calibrated with the new convection treatment of Canuto & Mazzitelli (1991) to MLT models. For each star, we find that the models mainly differ in the highest part of their convective envelope, where the temperature gradient and thus the temperature distribution are very sensitive to the convection treatment. The physical carateristics of the deeper layers remain unchanged.

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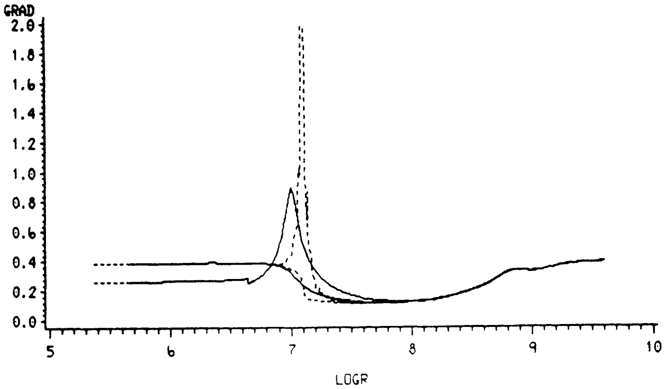

Figure 2: Temperature gradient (peaked curves) and adiabatic gradient as functions of log r (r beeing the distance to the surface, in cm) in a model of α Cen B calculated with MLT (solid line) and with the convection treatment of Canuto & Mazzitelli (1991; dashed line). The maximum value of the vertical axis is taken to be 2, but the temperature gradient calculated with the convection treatment of Canuto & Mazzitelli (1991) actually reaches the value of 8.

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