Entropy-calibrated modelling with CESTAM

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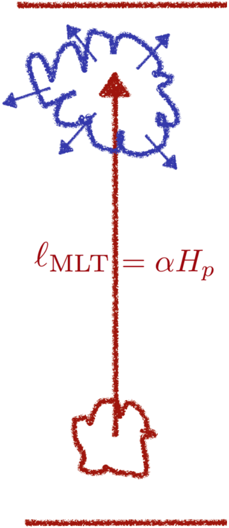
How do we model convection in 1D stellar evolution codes?

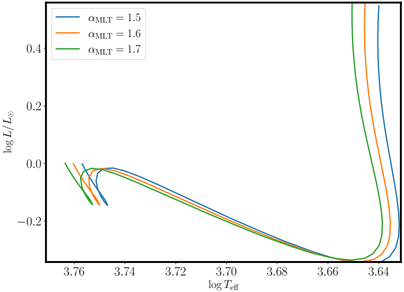


- Convection : extremely complex ⇒ *ad hoc* theories : MLT, CGM, ... ⇝ free parameter.
- MLT : Hot gas parcel rises to a height $\ell \propto \alpha_{\mathrm{MLT}} H_p$. α_{MLT} controls the convective flux.
- How do we choose α?
  - ▶ From calibration;
  - ▶ Compute grid of models with different α
  - ▶ Set to solar value;

Is there a more physical way to choose it?
Should α stays fixed along evolution?

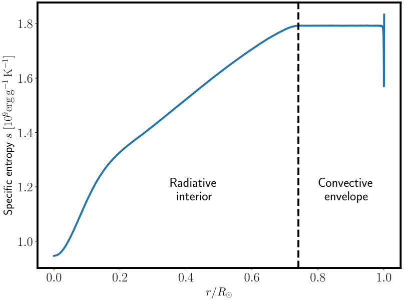
Can α be linked to other quantities?

α controls the stellar radius R.



$$L = 4\pi R^2 \sigma T_{\rm eff}^4$$

But R is also controlled by $s_{\rm ad}$, the entropy of the adiabat.



E.g., in a polytropic, completely convective model, (e.g. Ireland & Browning, 2018)

$$R \propto \exp\left(\frac{\gamma - 1}{3\gamma - 4}\frac{\mu s_{\rm ad}}{N_{\rm A} k_{\rm B}}\right)$$

Then α and $s_{\rm ad}$ are linked.

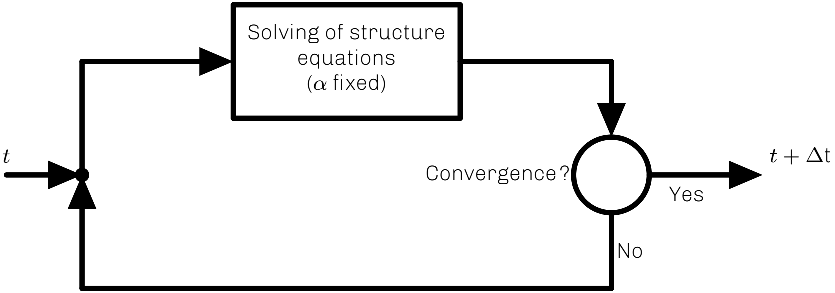
How do we know what $s_{\rm ad}$ a star should have?

• From precise 3D modelling of convective upper layers (stagger, CO5BOLD, ...). $s_{\rm ad}$ **is an input of the models.**
• Using grids of 3D atmospheres : prescription for $s_{\rm ad}$ as a function of $T_{\rm eff}, \log g, Z$.
• So far, three prescriptions :

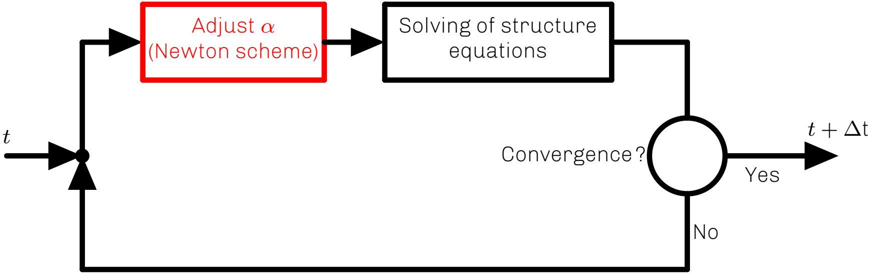
- Ludwig+99 : Based on 2D atm. models at fixed metallicity and with a chemical composition close to GS98 (proto-Sun).
- Magic+13 : Based on 3D atm. models (STAGGER grid). $[\mathrm{Fe/H}] \in [-4.0; +0.5]$. Chem. composition : $\simeq$ AGS09 (pres. Sun).
- Tanner+16 : Same as Magic+13 but with different mathematical form.

$\Rightarrow$ we can determine $s_{\rm ad}$ knowing $T_{\rm eff}, \log g$ and Z.
How do we relate α to $s_{\rm ad}$?

In a traditional stellar evolution code (e.g CESTAM ; Morel+95, Lebreton+08, Marques+13) :



Entropy-calibration, general idea (Spada+2018,2019,2021) :
The goal is to adjust α along evolution so that s_{ad} in 1D models matches s_{MHD} obtained from prescriptions.



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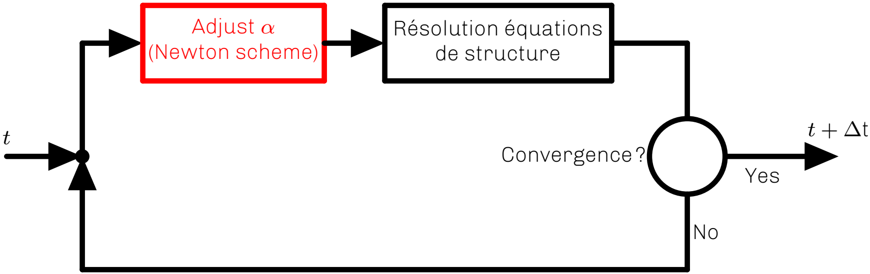
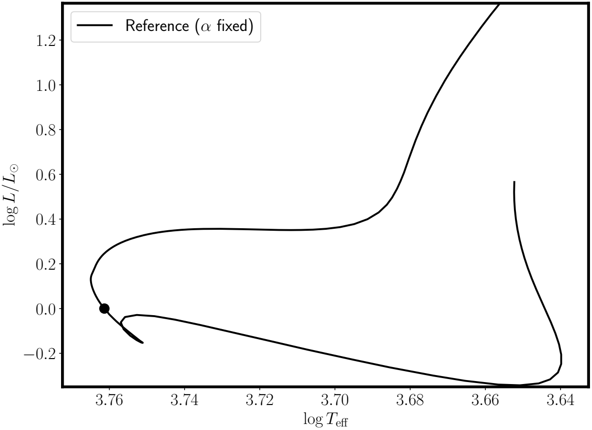


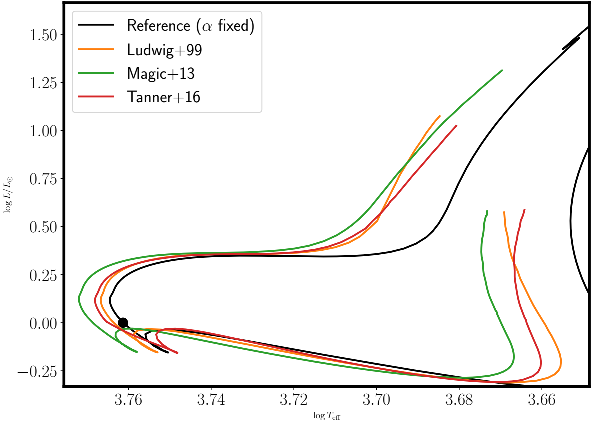
New implementation in CESTAM.
Why redo the work of Spada+ ?

- Different code (YREC (Demarque+08) $\rightarrow$ CESTAM). Different way of computing convective envelope ;
- Lot of care should be taken when using entropy prescriptions.

Gravitational settling, GS98.
Tuning of Y_0 and $\alpha_{\mathrm{MLT}}(\simeq 1.81)$ to obtain $T_{\mathrm{eff},\odot}$, $L_\odot$.



A first result



⇒ Large discrepancies ($\Delta T_{\rm eff} > 100$K).

It's different. Is it better?

Prescriptions should be corrected

- Entropy is defined up to a constant. EoS tables used in 2D and 3D MHD models and 1D evolution models are not the same.
  $\Rightarrow$ Addition of an offset $\mathrm{d}s$, computed using a reference model (Spada+2018,2019).
- The entropy varies with the chemical composition :

$$s \propto \frac{1}{\mu} \ln(\ldots) \tag{1}$$

  The mean molecular weight μ is different in MHD models and in your 1D model.
  $\Rightarrow$ Multiplicative factor $f_\mu = \mu_{\mathrm{RHD}}/\mu_{\mathrm{1D}}$ (Spada+2021).

Final corrected form :

$$s_{\mathrm{MHD}} \rightsquigarrow s_{\mathrm{MHD}} f_\mu + \mathrm{d}s \tag{2}$$

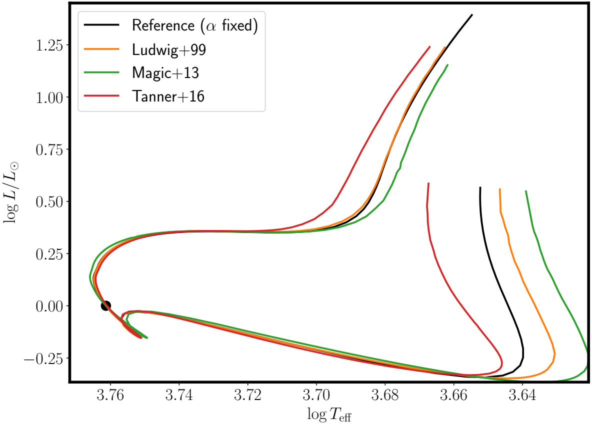
Prescriptions should be corrected

But also, prescription's coefficients from original paper should be used.

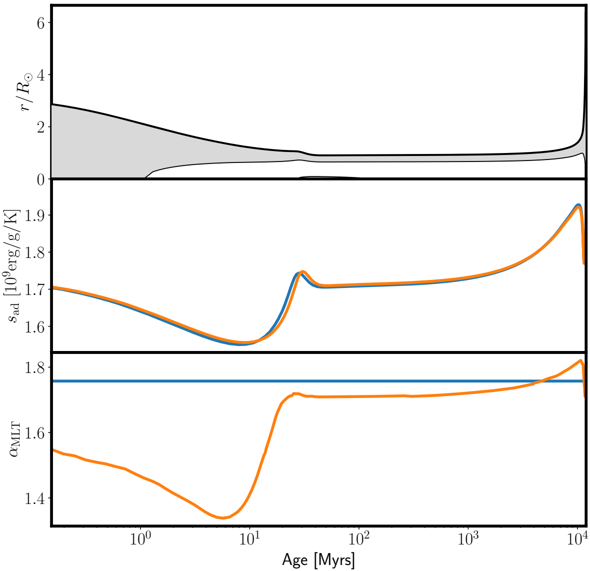
- Ludwig+99 Based on 2D models → less accurate adiabatic entropies
- Magic+13 & Tanner+16 : original paper used entropies at the bottom of the simulate box instead of s_{ad}

Using data from the CIFIST grid (computed with CO5BOLD : Ludwig+09 ; Freytag+12), we recalibrated all the parameters for the different prescriptions.

Better results



What is the cause of discrepancies during PMS and RGB?



$s \propto \ln T^{3/2}/\rho$
Virial th. : $T \propto R^{-1}$,
$\rho \propto R^{-3}$

- PMS : contraction phase.

$\Rightarrow s \searrow$

- RGB : expansion phase

$R \nearrow \Rightarrow s \nearrow$

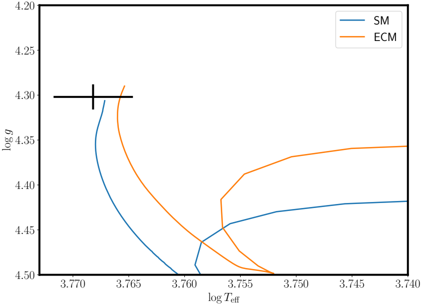
16Cyg A

- Observables (16 CygA; Karovicova+2021) :

$\log g$	$T_{\rm eff}$	$L/L_\odot$	[Fe/H]
4.302 ± 0.014	5864 ± 48	1.511 ± 0.0043	0.15 ± 0.05

- Calibration through Levenberg-Marquardt algorithm (OSM ; R. Samadi).
- Physics : AGS09, MLT, gravitational settling.
- Standard model (SM). Adjustable parameters : Age, M, $\alpha_{\rm MLT}$ (fixed), Y_0. Targets : $\log g$, $T_{\rm eff}$, $L/L_\odot$ and [Fe/H].
- Entropy-calibrated model (ECM). Adjustable parameters : Age, M, Y_0. Targets : $\log g$, $T_{\rm eff}$ and [Fe/H].

16Cyg A



	$\log g$	T_{eff}	$L/L_{\odot}$	[Fe/H]	
Obs.	4.302 ± 0.014	5864 ± 48	1.511 ± 0.0043	0.15 ± 0.05	
SM	4.306	5850	1.511	0.19	
ECM	4.290	5826	1.600	0.18	
	Age	M	α_{MLT}	Y_0	$R/R_{\odot}$
SM	7617	1.06 ± 0.01	2.02 ± 0.01	0.273 ± 0.004	1.20
ECM	6293 ± 939	1.10 ± 0.03	Varying	$0.267 \pm .002$	1.24

PLATO expected accuracies. Age :10%; Mass : 15%, Radius : 2%.

Conclusions

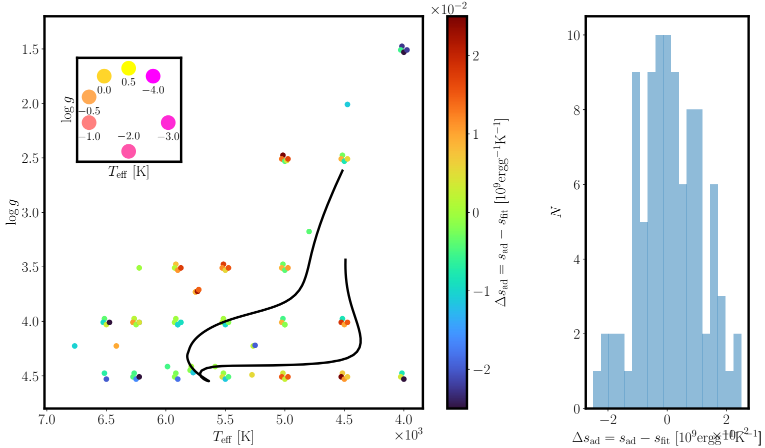
- Numerical scheme is robust and we recover results obtained by F. Spada with YREC.
- Sorted out the different prescriptions and improved them through corrections (see Manchon+, in prep for more details).
- Large impact for PLATO accuracy of model-dependent parameters.
- Changes PMS and RGB location of Solar type stars.
- Calibration independent of physics (contrary to prescription of α).

Now :

- More detailed tests on benchmark stars (seismic,...).
- What impact it has on depth of CZ ? Could have an impact on transport processes.

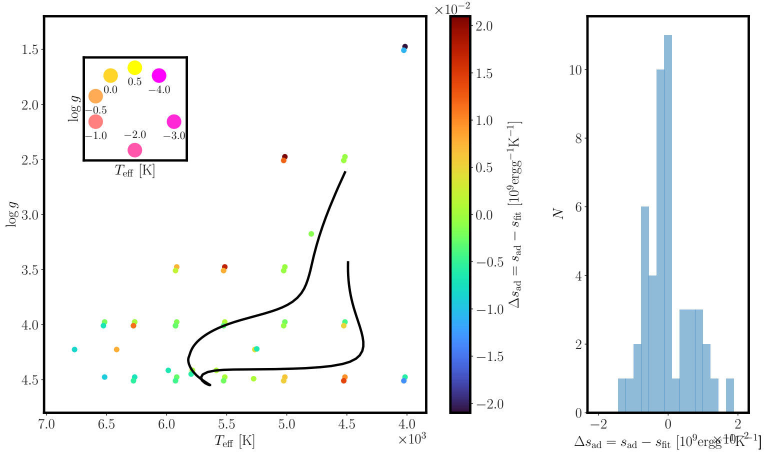
Prescription errors to $s_{\rm ad}$

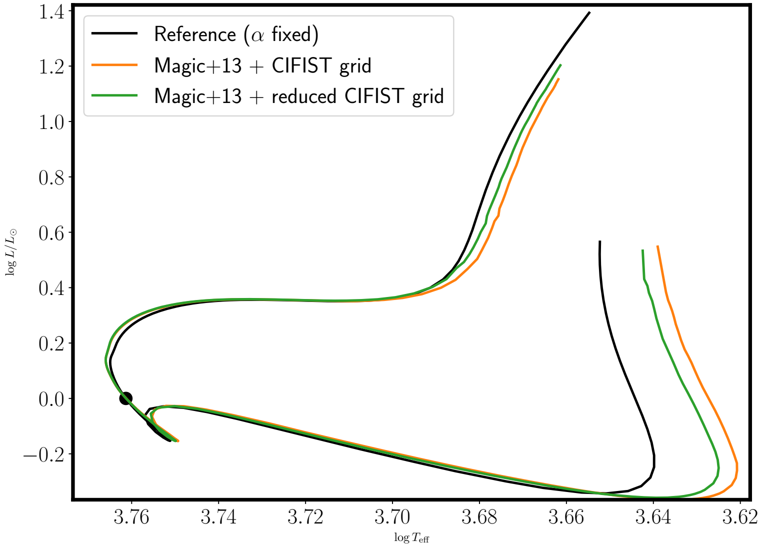
Error between Magic+13 prescription, with coefficients calibrated on the CIFIST grid



The CIFIST grid includes models with very low $[\mathrm{Fe/H}]$. What happens when we remove them?

Error between Magic+13 prescription, with coefficients calibrated on the CIFIST grid reduced to $-1.0 \geq [\mathrm{Fe/H}] \geq +0.5$:




Reference (α fixed)
Magic+13 + CIFIST grid
Magic+13 + reduced CIFIST grid
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
$\log L/L_\odot$
3.76
3.74
3.72
3.70
3.68
3.66
3.64
3.62
$\log T_{\rm eff}$