Delphine Hypolite
dhypolite@irap.omp.eu
Third year PhD student
Michel Rieutord , Bertrand Putigny

Modelling Achernar in 2D with the ESTER code

Introduction

Achernar, also known as α Eridani or HD10144, is a binary Be3V (Hitlner et al 1969) star of intermediate mass in rapid rotation. It has been the target of many observations owing to its impressive flattening $R_{eq}/R_p \sim 1.5$ (Domiciano de Souza et al. 2003) where R_{eq} is the equatorial radius and R_p the polar radius. Because it is also the closest (d = 42.75 pc, Hipparcos , van Leeuwen 2007) and brightest Be star around, Achernar has been candidate for high angular resolution and "long-baseline" interferometric observations in optic/IR (ESO-VLTI PIONER and AMBER). With additional spectroscopic, polarimetric and photometric observations Domiciano de Souza et al (2014) provide new estimate of the stellar parameters from the observations and the use of CHARRON models (e.g. Fig.1) which are presented in the following table 1

Stellar parameters of ACHERNAR

M	6.10 $M_\odot$
R_{eq}	9.16±0.23 $R_\odot$
R_{pol}	6.78 $R_\odot$
T_{eq}	12673 K
T_{pol}	17124 K
L	3019.952 $L_\odot$
V_{eq}	$298.8^{+6.9}_{-5.5}$ km/s
P_{eq}	1.55 days

TABLE 1 : Stellar parameters of Achernar deduced from observations, Domiciano de Souza & al (2014).

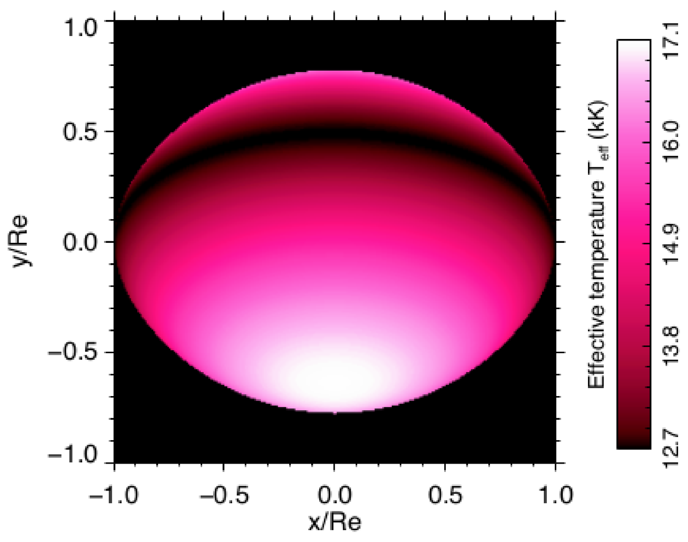

FIGURE 1 : Effective temperature of the best fit CHARRON model, Domiciano de Souza & al (2014).

Aim

We aim at reproducing the observed stellar parameters of Achernar and provide its structure and velocity field with the use of the ESTER code.

The ESTER code

The ESTER code (Espinosa Lara and Rieutord 2013), suitable for rotating Main Sequence intermediate mass stars, solves the following set of equations in the full compressible case in a spheroidal container (2D)

$$\Delta\phi = 4\pi G\rho \quad \text{Poisson equation}$$

$$\rho T\vec{v}\cdot\vec{\nabla}S = -\vec{\nabla}\cdot\vec{F} + \epsilon_* \quad \text{energy equation}$$

$$\rho(2\vec{\Omega}_*\wedge\vec{v} + \vec{v}\cdot\vec{\nabla}\vec{v}) = -\vec{\nabla}P - \rho\vec{\nabla}(\phi - \frac{1}{2}\Omega_*^2 s^2) + \vec{F}_{viscous} \quad \text{momentum equation}$$

$$\vec{\nabla}\cdot(\rho\vec{v}) = 0 \quad \text{mass conservation equation}$$

where $\vec{F}$ the energy flux

$$\vec{F} = -\chi_r\vec{\nabla}T - \frac{\chi_{turb}T}{\mathcal{R}_M}\vec{\nabla}S \qquad (1)$$

and ϵ_* is the nuclear energy production rate which is tabulated along with the density and opacity fields

$$P \equiv P(\rho, T) \quad \text{OPAL} \qquad (2)$$

$$\kappa \equiv \kappa(\rho, T) \quad \text{OPAL} \qquad (3)$$

$$\epsilon_* \equiv \epsilon_*(\rho, T) \quad \text{NACRE} \qquad (4)$$

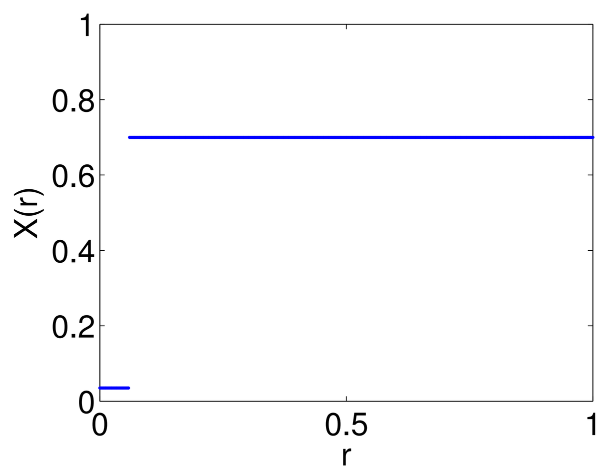

FIGURE 2 : Abundance of hydrogen profile.

Decreasing X_c, the core fraction of H, describes the evolution of the star along the Main Sequence.

Conclusion

According to 1D stellar evolutionnary paths and Main-Sequence ESTER models, Achernar could be beyond the ZAMS but the gravitational contraction energy law (5) could not reproduce the stellar parameters of Achernar. The abundance of hydrogen profile is thought to be a key feature in advanced evolution stages along and post Main-Sequence. We did not so far provide a consistent post Main-Sequence model matching all Achernar's stellar parameters but we lately implemented the nuclear timescale evolution in the ESTER code with the use of CESAM2k routines (Morel 1997). This allows the derivation of realistic self-computed abundance of hydrogen profiles → New models to come !

Main Sequence models and gravitational contraction models

The first column of the table provides the features of a 6.1$M_\odot$ ESTER Main Sequence model. The computed shape is smaller and effective temperature higher than the values of table 1 indicating that standard Main Sequence models do not reproduce the observations.

	ESTER models	
	Main Sequence	Gravitational contraction
Mass ($M_\odot$)	6.10	6.10
R_{eq} ($R_\odot$)	3.544	9.468
R_{pol} ($R_\odot$)	3.136	6.93
T_{eq} (K)	16899.65	9511.57
T_{pol}(K)	19105.89	13013.11
L ($L_\odot$)	1040.323	1014.456
V_{eq} (km/s)	295.18	294.57
P_{eq} (days)	0.607	1.626
P_{pol} (days)	0.716	1.651
$X_{env.}$	0.70	0.70
$X_{core}/X_{env.}$	0.05	0.05
Z	0.05	0.014

TABLE 2 : Stellar parameters of a 6.1$M_\odot$ ESTER models. Fist column is the steady state and the second one is using the gravitational contraction energy law (5).

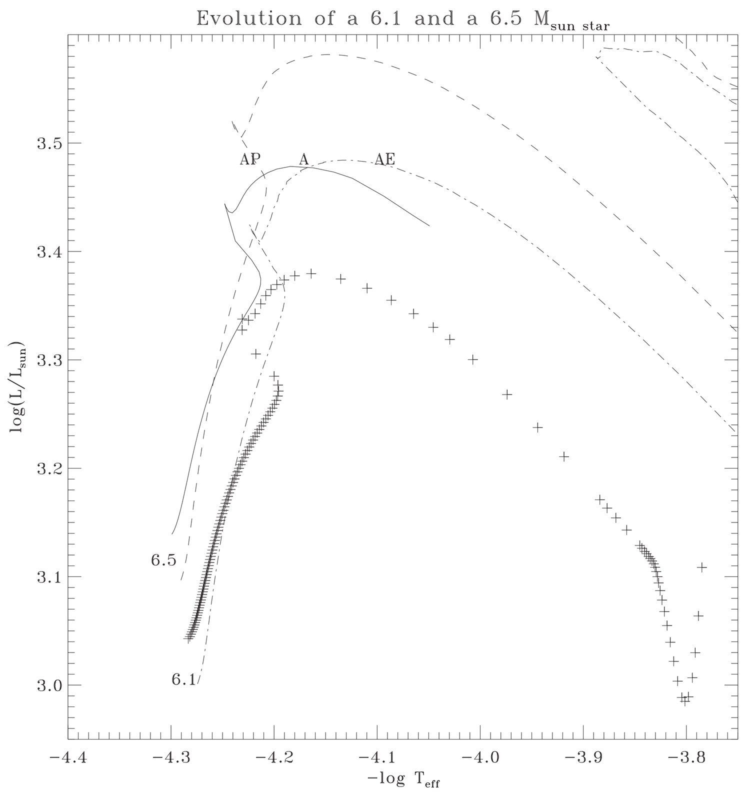

FIGURE 3 : Evolutionary paths of 6.1$M_\odot$ and 6.5$M_\odot$ models from CESAM2k (Morel 1997) and SYCLIST (Geneva code (Georgy 2014)). AP is the observed polar temperature of Achernar, AE the equatorial value and A the mean of both.

→ Achernar could be more evolved, crossing the Hertzprung's gap
→ its core undergoing a gravitational contraction (expectation of larger and cooler envelope)
→ 2^{nd} column of the table () : best ESTER model resulting from the switch of ϵ_* in the energy equation by a gravitational contraction energy law from Maeder (2009)

$$\epsilon_{grav} = -\frac{3}{5}c_P T\frac{\dot{R}}{R} \qquad (5)$$

→ Even if we can recover the observed radius, the temperature does not match with the observations for any converging $\dot{R}$ contraction rate.

Impact of a gradient of composition within the envelope and best model so far with a stairstep abundance of hydrogen profile

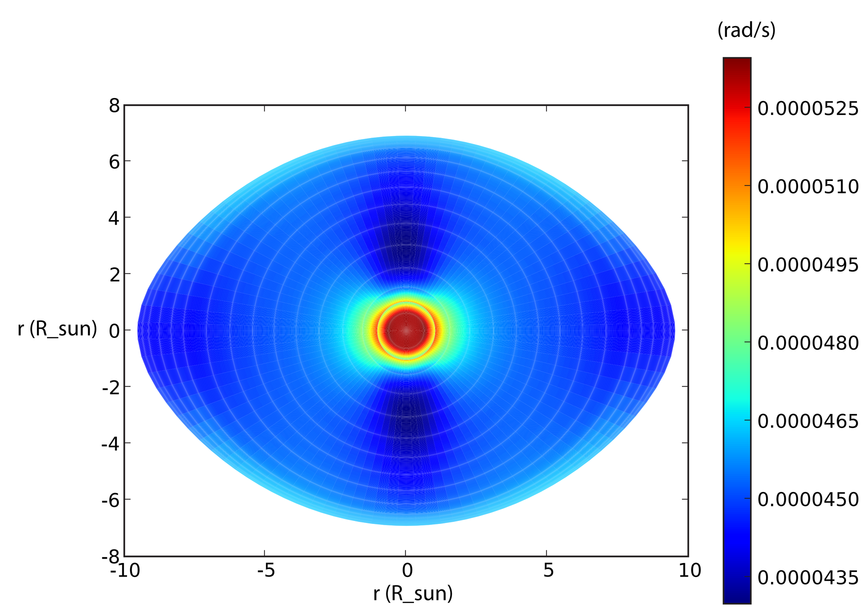

FIGURE 4 : Meridional view of the differential rotation (rad.s^{-1}) of a 6.1$M_\odot$ ESTER model using a stairstep profile of hydrogen.

	ESTER model with $X = f(r)$
Mass ($M_\odot$)	6.10
R_{eq} ($R_\odot$)	9.536
R_{pol} ($R_\odot$)	6.917
T_{eq} (K)	13089.22
T_{pol}(K)	17948.88
L ($L_\odot$)	2933.206
V_{eq} (km/s)	293.51
P_{eq} (days)	1.643
P_{pol} (days)	1.571
$X_{env.}$	0.70
$X_{core}/X_{env.}$	0.47
Z	0.046

TABLE 3 : Stellar parameters of a 6.1$M_\odot$ ESTER model with a modified chemical composition.

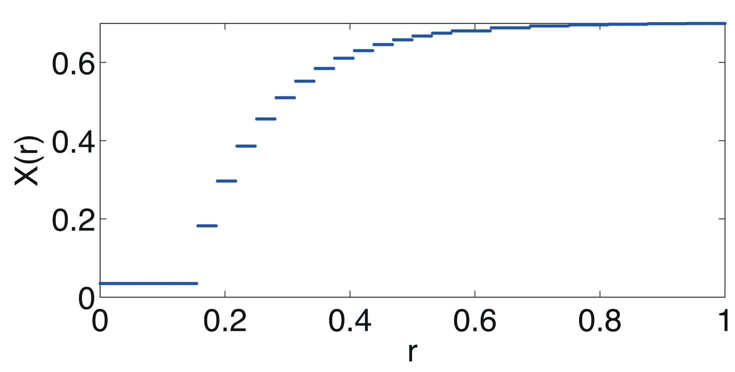

FIGURE 5 : Stairstep profile of H abondance.

We smooth the composition gradient at the core-envelope interface to suppress the discontinuity on the abundance of hydrogen profile and get a more realistic profile of thermic energy with the use of the function

$$X(r) = X_{core}X_{env} + X_{env}(1 - X_{core})\left(1 - e^{1-R_*/R_c}\right)^{-1}\left(1 - e^{1-r/R_c}\right) \quad . \qquad (6)$$