

PRESENT STATUS OF TWO-DIMENSIONAL ESTER MODELS: APPLICATION TO BE STARS

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Abstract. ESTER two-dimensional models solve the steady state structure of fast rotating early-type stars including the large scale flows associated with the baroclinicity of the radiative zones. Models are compared successfully to the fundamental parameters of the two main components of the triple system δ Velorum that have been derived from interferometric and orbit measurements. Testing the models on the Be star Achernar (α Eri), we cannot reproduce the data and conclude that this star has left the main sequence and is likely crossing the Hertzsprung gap. Computing main sequence evolution of fast rotating stars at constant angular momentum shows that their criticality increases with time suggesting that the Be phenomenon and the ensuing mass ejections is the result of evolution.

Keywords: Stellar models, Rotation, Be stars

1 Introduction

One of the grand challenges of stellar modelling is the design of realistic models for fast rotating stars. Many observational data either from interferometry, from asteroseismology, from spectroscopy (chemical abundances) require models that are not limited to small rotation rates. These models are necessarily two-dimensional because these stars are no longer spherically symmetric and also because they are pervaded by large-scale fluid flows (differential rotation and meridional circulation) that are key elements to understand their chemical and dynamical evolution.

Here, we wish to give a brief presentation of the first results of the ESTER project, its promises as far as interpretation of data are concerned and its future developments.

2 The physical content of ESTER models

Present ESTER models are describing the internal structure of an isolated fast rotating star in a steady state. No time evolution is included and only early-type stars (mass larger than $1.7 M_{\odot}$) can be computed. The modeling of an outer convection zone is still a problem that needs to be solved. The central convective core is assumed to be isentropic. With these prerequisites ESTER models solve the four following partial differential equations:

$$\begin{cases} \Delta\phi = 4\pi G\rho \\ \rho T\vec{v} \cdot \vec{\nabla} S = -\text{Div}\vec{F} + \varepsilon_* \\ \rho(2\vec{\Omega}_* \wedge \vec{v} + \vec{v} \cdot \vec{\nabla}\vec{v}) = -\vec{\nabla}P - \rho\vec{\nabla}(\phi - \frac{1}{2}\Omega_*^2 s^2) + \vec{F}_v \\ \text{Div}(\rho\vec{v}) = 0. \end{cases} \quad (2.1)$$

where we recognize the Poisson, entropy, momentum and continuity equations respectively. They are completed by the microphysics from OPAL and NACRE (opacities, equation of state and reaction rates). Boundary conditions are stress-free for the velocity field and match black body radiation for temperature (see Rieutord & Espinosa Lara 2013; Espinosa Lara & Rieutord 2013, for details).

The equations are solved using the discretization of spectral elements in the radial direction with Chebyshev polynomial (fluid layers are of spheroidal shape). The horizontal coordinate uses the decomposition in spherical harmonics. Various tests measure the quality of the numerical solution. The ESTER code is under GNU public license and can be downloaded at <http://code.google.com/p/ester-project>.

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Table 1. Comparison between observationally derived parameters of the stars and tentative two-dimensional models. Data from δ Vel are from Mérand et al. (2011), those of Achernar are from Domiciano de Souza et al. (2012). The models compare nicely with observationally constrained data for the two components of δ Vel A (an eclipsing binary) but have difficulties with Achernar. Here ε is the flatness, ω_k the ratio of the equatorial angular velocity to the keplerian one, j is the mean specific angular momentum of the star and $X_{\text{env.}}$ is the hydrogen mass fraction in the envelope.

Star	Delta Velorum Aa		Delta Velorum Ab		Achernar (α Eri)	
	Observations	Model	Observations	Model	Observations	Model
Spectral type	A2 IV		A4 V		B4 Ve	
Mass (M_{\odot})	2.43 ± 0.02	2.43	2.27 ± 0.02	2.27		8.20
R_{eq} (R_{\odot})	2.97 ± 0.02	2.95	2.52 ± 0.03	2.52	11.6 ± 0.3	11.5
R_{pol} (R_{\odot})	2.79 ± 0.04	2.77	2.37 ± 0.02	2.36	8.0 ± 0.4	7.9
ε		0.061		0.064		0.310
ω_k		0.36		0.37		0.92
i	90°		90°		101°	
T_{eq} (K)	9450	9440	9560	9477	9955^{+1115}_{-2339}	11250
T_{pol} (K)	10100	10044	10120	10115	18013^{+141}_{-171}	16800
L (L_{\odot})	67 ± 3	65.2	51 ± 2	48.5	4500 ± 300	3700
V_{eq} (km/s)	143	143	150	153	298 ± 9	339
j (10^{17} cm ² /s)		1.02		0.98		5.33
k [$j/R_{\text{eq}}^2 \Omega_{\text{eq}}$]		0.0348		0.0363		0.0196
P_{eq} (days)		1.045		0.832		1.72
P_{pol} (days)		1.084		0.924		1.68
$X_{\text{env.}}$		0.70		0.70		0.74
$X_{\text{core}}/X_{\text{env.}}$		0.10		0.30		0.05
Z		0.011		0.011		0.04

3 Results

3.1 Modeling stars observed with optical or infra-red interferometers

In Tab. 1 we show a comparison between ESTER models and two main sequence stars Aa and Ab of δ Velorum. The two stars are members of a binary system but their wide separation makes the tides of weak influence. We first note that the model parameters nicely fit those derived from the interferometric (and orbit) data even if for such stars some surface convection should be expected (but it is not efficient enough to alter the radii). These two stars are coevolving. We note that the most massive has less hydrogen in its core as expected and that both require the same metallicity also as expected. We note that their mean specific angular momentum (angular momentum per unit mass) is quite the same putting interesting constraints on the dynamics of the formation of this system.

3.2 Achernar and Be stars

The case of the Be star Achernar (α Eri) is quite interesting. It has been much observed with infra-red interferometry at VLTI (e.g. Domiciano de Souza et al. 2012, and references therein) since it is the nearest Be star. As may be seen, ESTER models are not performing as well as for δ Velorum, especially on the mass determination. Indeed, it is known that Achernar is a binary star where the companion is an A-type star orbiting the actual Be star in 15 yrs (Kervella et al. 2008). Mass inferences of Achernar A is near $6.1 M_{\odot}$ (Domiciano de Souza, private communication) clearly below our value. This discrepancy may be of various origin: (i) it may well be that Achernar has left the main sequence and is crossing the Hertzsprung gap, a configuration that is beyond reach of ESTER models at the moment, or (ii) presently observed values are perturbed somehow by circumstellar material including the companion. We give in Fig. 1 the expected view of this star according to the best estimate of the ESTER models.

ESTER models can also be used to mimic evolution of early-type stars by decreasing the hydrogen content of the convective core. For stars that do not lose angular momentum, we can examine the evolution of the

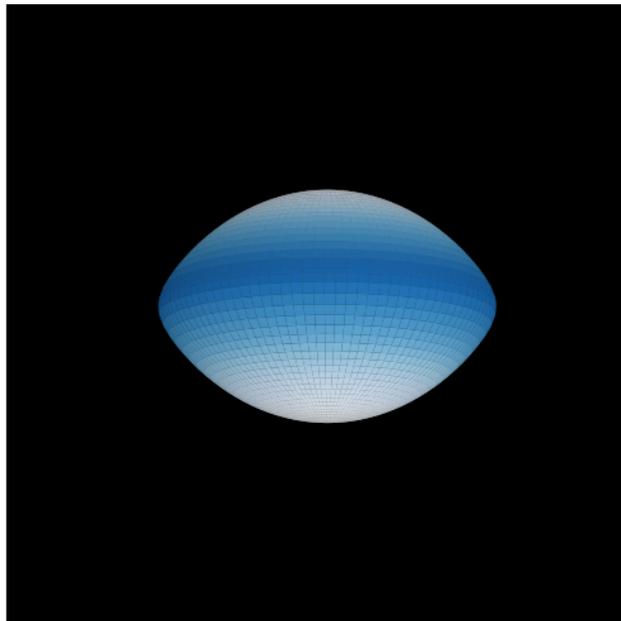


Fig. 1. A view of the surface brightness (the local flux) of Achernar with the model of Tab. 1 (values are derived from Domiciano de Souza et al. 2012).

ratio of angular velocity to critical angular velocity (which we call the Ω -criticality). According to Zorec & Royer (2012) and Alecian et al. (2013), A-type stars lose a negligible amount of angular momentum and this is probably the case for late B-type stars. In the case of zero-angular momentum loss, Fig. 2 shows the evolution of Ω -criticality when the star evolves along the main sequence. We consider a $7 M_{\odot}$ model of solar metallicity that initially rotates at $V_{\text{eq}} = 350$ km/s ($R_{\text{eq}}/R_{\text{pol}} = 1.17$). This result suggests that Be stars result from the evolution of initially fast rotating B stars. Mass-loss may complicate the view, but our models show that initially fast rotating B-stars will inevitably reach critical rotation if mass loss is weak enough.

4 Conclusions

Present ESTER models can describe rather faithfully rapidly rotating early-type main sequence stars. They therefore can be used to interpret interferometric and asteroseismic data. In this latter case, they need to be completed by a code that can deal with rotation non-perturbatively (presently two codes do this job: TOP of Reese et al. (2009) and ACOR of Ouazzani et al. (2012)).

In the future, development of ESTER should include time evolution either from chemical evolution or from gravitational contraction so as to be able to describe early-type stars from the birthline to the giant state. In parallel, the other challenge is to include outer convection zone so as to be able to describe low-mass solar type stars.

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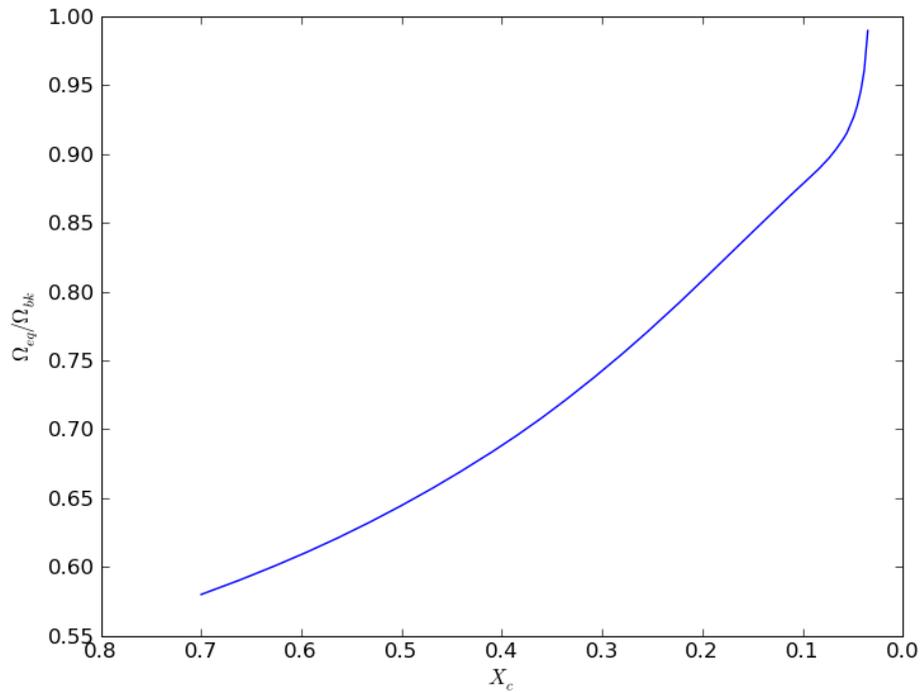


Fig. 2. Equatorial angular velocity divided by the keplerian angular velocity at equator as a function of the hydrogen mass fraction of the star for a constant total angular momentum. Metallicity is solar and $M=7 M_{\odot}$.

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