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Two-dimensional models of early-type fast rotating stars: the ESTER project

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Abstract. In this talk I present the latest results of the ESTER project that has taken up the challenge of building two dimensional (axisymmetric) models of stars rotating at any rotation rate. In particular, I focus on main sequence massive and intermediate mass stars. I show what should be expected in such stars as far as the differential rotation and the associated meridional circulation are concerned, notably the emergence of a Stewartson layer along the tangent cylinder of the core. I also indicate what may be inferred about the evolution of an intermediate-mass star at constant angular momentum and how Be stars may form. I finally give some comparisons between models and observations of the gravity darkening on some nearby fast rotators as it has been derived from interferometric observations. In passing, I also discuss how 2D models can help to recover the fundamental parameters of a star.

Keywords. Stars, rotation

1. Introduction

Rotation has now become an unavoidable parameter of stellar models, but for most massive or intermediate-mass stars rotation is fast, at least of a significant fraction of the critical angular velocity. Current spherically symmetric models try to cope with this feature of the stars using various approximations, like for instance the so-called shellular rotation usually accompanied with a diffusion that is meant to represent the mixing induced by rotationally generated flows. Such approximations may be justified in the limit of slow rotation where anisotropies and associated flows are weak (Zahn 1992). However, when rotation is fast, say larger than 50% of the critical velocity the use of a spherically symmetric 1D-model is doubtful. This is not only because of the centrifugal flattening of the star, but also because of the flows that are induced by the baroclinic torque that naturally appears when the stable stratification of a radiative region meets rotation. These flows face the cylindrical symmetry of the Coriolis force and the spheroidal symmetry of the effective gravity.

The breaking of spherical symmetry is also to be taken into account when the early-type star at hands show delta Scuti type oscillations, like α Aql or α Oph actually do (Monnier *et al.* 2010). The modelling of these seismic data requires 2D models (Reese *et al.* 2006). In the same line, more than half a dozen of nearby early-type stars, showing fast rotation, have been observed with interferometers (e.g. Che *et al.* 2011). Here too, 1D models are not usable for data processing.

Hence, for all these stars 2D models are crucial. Rotation is actually the main phenomenon that breaks the spherical symmetry on the large scales. It can be properly accounted for with axisymmetric 2D models.

The challenge of computing 2D models, which unlike previous attempts include the

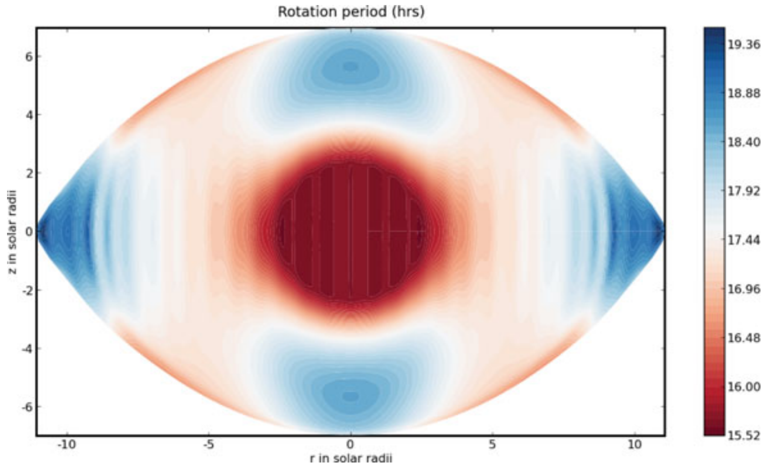

Figure 1. Differential rotation of a 30 $M_\odot$ star rotating at 98% of the critical angular velocity. The star is homogeneous chemically with X=0.7 and Z=0.02.

large-scale flows, has been taken up with the ESTER project†. The first 2D models from this project are giving the structure of an early-type star including its differential rotation and the associated meridional circulation (Espinosa Lara & Rieutord 2013). We recall that these flows are consubstantial to rotating stars and are driven by the baroclinicity of the radiative envelope (Rieutord 2006). We show in Fig. 1 the shape of the differential rotation of a massive star rotating almost critically. Such results show that baroclinic flows generated by rotation are complex and far from the one-dimensional shellular rotation imposed in the 1D set-up. The comparison of 2D models and interferometric data has been particularly successful (Rieutord 2013; Domiciano de Souza *et al.* 2014), showing that gravity darkening can be nicely modeled by a simple law much better than with von Zeipel rule (Espinosa Lara & Rieutord 2011; Rieutord 2015).

Present ESTER models compute the steady state of an isolated non-magnetic early-type star. The next step is to implement time-dependence so as to be able to compute genuine stellar evolution in two-dimensions. The ultimate evolution of the code will be the shift to 3D models allowing large-scale magnetic fields and/or tidal distortion to be included.

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† `http://ester-project.github.io/ester/`