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Differential rotation in early type stars

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Abstract. Using 2D models of rotating stars, the interferometric measurements of α Eri and its fundamental parameters corrected for gravitational darkening effects we infer that the star might have a core rotating 2.7 times faster than the surface. We explore the consequences on spectral lines produced by surface differential rotation combined with the effects due to a kind of internal differential rotation with rotational energies higher than allowed for rigid rotation which induce geometrical deformations that do not distinguish strongly from those carried by the rigid rotation.

1. Models of internal differential rotation. The case of αEri

An initial rigid rotation in the ZAMS switches in some 10^4 yr into an internal differential rotation (IDR) (Meynet & Maeder 2000, MM2000). Nothing precludes then that IDR be present since the pre-main sequence phases implying a total angular momentum higher than allowed for rigid rotation. Inspired by the internal rotation laws obtained in MM2000, we adopt the step-like rotational law: $\Omega(\varpi) = \Omega_{\rm co}[1 - p.e^{-a.\varpi^b}]$, where $\varpi =$ distance to the rotation axis; $\Omega_{\rm co} =$ core angular velocity; p determines $\Omega_{\rm co}/\Omega_{\rm surf}$; $a = c(r_{\rm co})$ where $r_{\rm co} = R_{\rm core}/R_{\rm eq} =$ distance at which $\Omega = (1/2)\Omega_{\rm co}$; b determines the steepness of the drop from $\Omega_{\rm co}$ to $\Omega_{\rm surf}$. From MM2000 we adopt $b=5$, so that the rotational law is stable against axi-symmetric perturbations $[\partial j/\partial\varpi > 0;\ j = \Omega(\varpi)\varpi^2]$ for $p \lesssim p_{\rm max}(b=5) = 0.73$. The geometrical deformation of stars is obtained by solving the 2D Poisson equation (Clement 1979):

$$\Delta\Phi_G(\theta, \varpi) = -4\pi\rho(\theta, \varpi) \tag{1}$$

using barotropic relations $P = P[\rho(r)]$ of stellar interiors without rotation in different evolutionary stages (Zorec et al. 1989, Zorec 1992). Fig. 1a shows stellar meridian cuts for $\eta = \Omega^2_{\rm surf} R^3_{\rm eq}/GM$, several values of p and $r_{\rm co} = 0.2$. Fig. 1b shows $R_{\rm eq}/R_o$ ($R_o =$ stellar radius at rest) against $\tau_d = \mathcal{K}/|\mathcal{W}|$ ($\mathcal{K} =$ rotational energy; $\mathcal{W} =$ gravitational potential energy).

We considered that the apparent polar radius $R^{\rm app}_{\rm po}$ of α Eri is well determined (Domiciano de Souza et al. 2003, Vinicius et al. 2005), while the equatorial radius $R_{\rm eq}$ is obtained by asking the equivalent circular (determined spectrophotometrically and from visible interferometry) and the actual elliptical areas of the apparent stellar disc be equal. The relation between apparent and true stellar radii ratios: $R^{\rm app}_{\rm po}/R_{\rm eq} = \{1 - [1 - (R^{\rm true}_{\rm po}/R_{\rm eq})^2]^2 \sin^2 i\}^{\frac{1}{2}}$ leads to

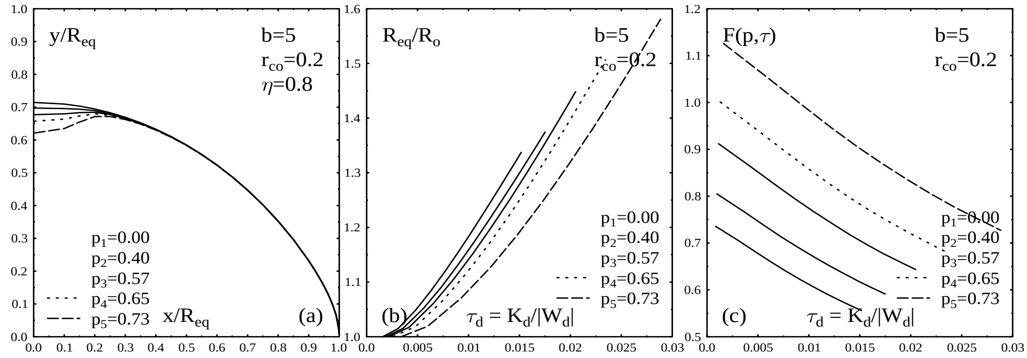

Figure 1. a) Meridian cuts of models with $b = 5$, $r_{\rm co} = 0.2$, $\eta = 0.8$ and several values of p. b) Equatorial radius $R_{\rm eq}/R_o$ against $\tau_d = K/|W|$ and p. c) Function $F(p, \tau_d)$ against τ_d and p

$F(p, \tau)$ that can be evaluated with observed quantities and whose theoretical counterpart is (see Fig. 1c):

$$F(p, \tau) = \left[1 - (R_{\rm po}/R_{\rm eq})^2\right] / \left(V_{\rm e}/V_{\rm c,r}\right)^2 \tag{2}$$

where $V_{\rm eq}$ = equatorial velocity; $V_{\rm c}$ = critical velocity at rigid rotation. Thanks to interferometric data, we can look for models that reproduce the following observables: $R_{\rm eq}/R_{\odot}$, $R_{\rm eq}/R_{\rm po}$, $V \sin i$ corrected for gravity darkening effects (Frémat et al. 2005) and $F(p, \tau_d)$. Thus, we infer:

$$\left.\begin{array}{rclrclrcl} p &=& 0.624 \pm 0.001 & \tau &=& 0.014 \pm 0.001 & i &=& 52^o \\ \eta &=& 0.69 \pm 0.07 & V_{\rm eq} &=& 308 \pm 16 {\rm km/s} & \Omega_{\rm co}/\Omega_{\rm surf} &=& 2.7 \end{array}\right\} \tag{3}$$

For rigid rotation it is $p = 0.0$ and $\tau_d \lesssim 0.015$.

2. Combined effects of internal and surface differential rotations on spectral lines

The emitted spectrum of a differential rotator depends sensitively on the value of $R_{\rm core}/R_{\rm eq}$. Fig. 2(left) shows spectral lines in the $\lambda\lambda 4250 - 4490$ Å interval produced by a star [rest $T_{\rm eff} = 20000$ K, $\log g = 3.5$] with a surface at rigid rotation, $V_{\rm surf} \sin i = 360$ km s^{-1}, $\eta = 0.95$, $p = 0.7$ (*dots* = spherical star without gravitational darkening (GD); *bold black* = rigid rotator with GD; *thin black* = differential rotator with $r_{\rm co} = 0.3$; *grey* = differential rotator with $r_{\rm co} = 0.2$. If we consider that the angular velocity against the co-latitude θ is:

$$\Omega_{\rm surf}(\theta) = \Omega_{\rm surf,eq}(1 - \alpha \cos^2 \theta) \tag{4}$$

and use the same parameters as in Fig. 2(left) but $\alpha \neq 0$ we obtain the line profiles shown in Fig. 2(right) (*dots* = no GD and $\alpha = 0.0$; *bold black* = GD+$\alpha = 0.0$; *thin black* = GD+$\alpha = 0.5$; *grey* = GD+$\alpha = -0.5$). We can show that for $R_{\rm core}/R_{\rm eq} \rightarrow 0$ an apparent rigid rotation regime is recovered, but for a higher τ_d

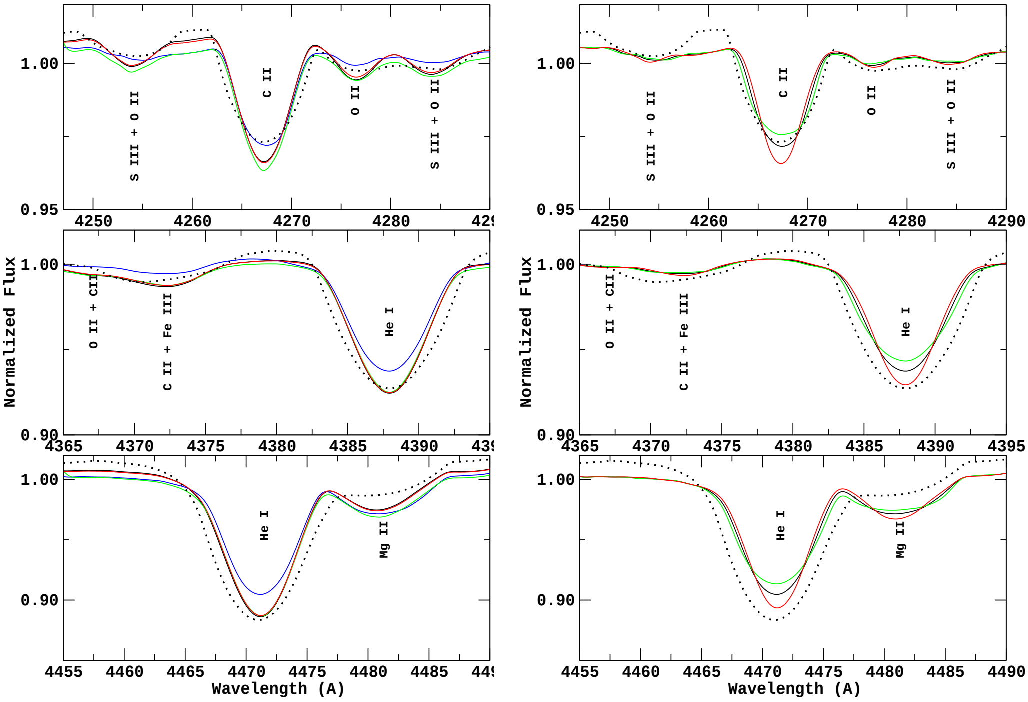

Figure 2. (left) Synthetic spectra produced by a star with a surface at rigid rotation, $V_{\rm surf} \sin i = 360$ km/s, $\eta = 0.95$, $p = 0.7$ [rest $T_{\rm eff} = 20000$ K, $\log g = 3.5$] (*dots*= spherical and no GD; *bold black*= rigid rotator with GD; *thin black*= IDR with $r_{\rm co} = 0.3$; *grey*= IDR with $r_{\rm co} = 0.2$. (right) Spectra from the same star as in the left but including surface differential rotation: *dots* = no GD and $\alpha = 0.0$; *bold black* = GD+$\alpha = 0.0$; *thin black* = GD+$\alpha = 0.5$; *grey* = GD+$\alpha = -0.5$)

ratio. According to τ_d a given line equivalent width may imply different stellar fundamental parameters. The sensitivity to the stellar deformation and to the related GD depends on the spectral line and the inclination i. Due to a higher change of the polar radius and consequent higher local effective temperatures than for a rigid rotation, lines can be deepened, shallowed, or self-reversed. The differences in the equivalent widths carry uncertainties on the chemical abundance determinations. The surface differential rotation in gravity darkened stars carry deepening of line profiles if $\alpha < 0$ and they are shallowed if $\alpha > 0$. Other related subjects can be found in http://www2.iap.fr/users/zorec/.

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