Evolution of rotation in rapidly rotating early-type stars during the main sequence with 2D models.

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Figures from soon to be submitted Gagnier, D., Rieutord, M., Charbonnel, C., Putigny, B. and Espinosa Lara, F. 2018a&b

1. Introduction

The evolution of the rotation rate of stars is one of the open challenges of nowadays stellar physics. The rotation rate of a star indeed depends on several un-mastered aspects of stellar physics. The most important one may be the transport of angular momentum and in the first place the losses due to radiatively or magnetically driven winds. Angular momentum losses depend on various phenomena but in particular on the mass-loss distribution at the surface of the star. When early-type stars are considered, one often faces fast rotation, the shape of these stars strongly deviates from the spherical symmetry and thus emphasizes the anisotropy of the wind. With ESTER 2D-models we have now access to the latitude variations of surface quantities that matter for mass-loss, we can thus investigate in some details the consequences of the ensuing anisotropic radiative winds.

2. The ESTER code

The ESTER code computes the steady state of an isolated rotating star, including the large-scale flows driven by the baroclinicity of the radiative regions. It solves in 2D (assuming axisymmetry) the steady equations of stellar structure with fluid flows

$$\Delta\phi = 4\pi G\rho$$

$$\boldsymbol{\nabla}\cdot\rho\boldsymbol{v} = 0$$

$$\rho\boldsymbol{v}\cdot\boldsymbol{\nabla}\boldsymbol{v} = -\boldsymbol{\nabla}P - \rho\boldsymbol{\nabla}\phi + \boldsymbol{F}_{\rm visc}$$

$$\begin{cases} \rho T\boldsymbol{v}\cdot\boldsymbol{\nabla}s = \boldsymbol{\nabla}\cdot(\chi\boldsymbol{\nabla}T) + \epsilon_* & \text{in radiative env.} \\ \partial_r s = 0 & \text{in convective core} \\ + \text{ boundary conditions} & \end{cases}$$

- Opacity and EOS given by OPAL tables with GN93 mixture
- Diffusive transport of momentum insured by $\nu \to 0$
- Analytical formula for nuclear energy generation (pp- & CNO cycles)

3. The $\Omega\Gamma$-limit

The $\Omega\Gamma$-limit is reached when $\boldsymbol{g}_{\rm tot} = \boldsymbol{0}$ somewhere on the stellar surface of rapidly rotating early-type stars. It is associated with a critical angular velocity Ω_c.

$$\boldsymbol{g}_{\rm tot} = \boldsymbol{g}_{\rm eff}\left[1 - \Gamma_\Omega(\theta)\right]$$

with $\Gamma_\Omega(\theta)$ the local rotation-dependent Eddington parameter

$$\Gamma_\Omega(\theta) = \frac{\kappa(\theta)L}{4\pi cGM}\,\frac{\tan^2(\psi(r,\theta))}{\tan^2\theta}$$

which is maximum at the equator: criticality reached when $\Gamma_\Omega(\pi/2) = 1$. This corresponds to

$$\Omega_c^2 = \Omega_k^2\left[1 - \Gamma(\pi/2)^{3/2}\right]$$

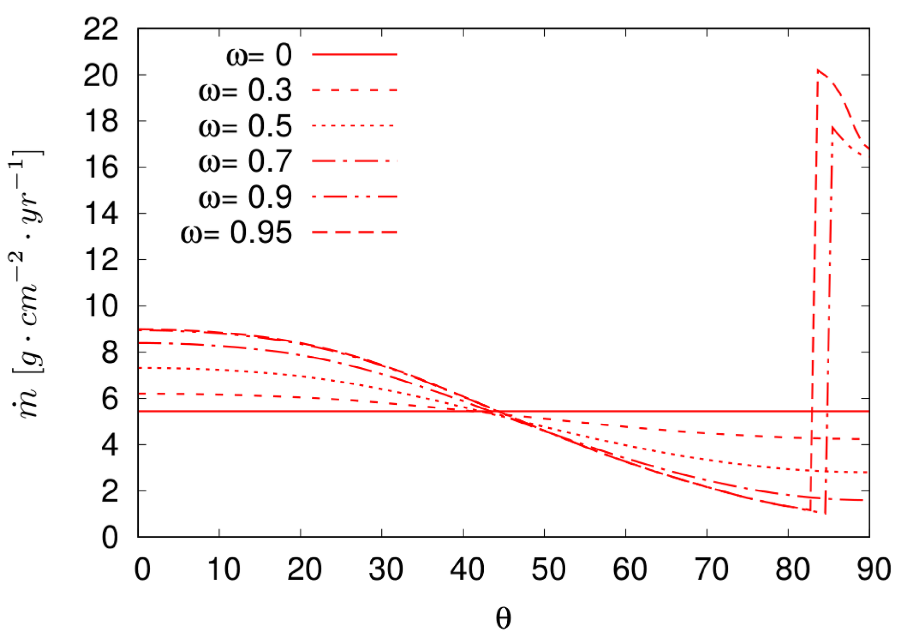
Because of gravity darkening, the difference between Ω_c and Ω_k never exceeds 4% for $M \leq 40\ M_\odot$ models.

4. A local mass-flux prescription

Assumptions : Wind is an isothermal stationary flow driven outward by photon absorption, the local mass-flux follows the same scaling as the CAK mass loss rate in the non-rotating regime

$$\dot{m}(\theta) = \frac{4}{9}\frac{\alpha k^{1/\alpha'}}{v_{\rm th}(\theta)c}\left[\frac{c}{\kappa_e(1-\alpha)}\left(g_{\rm eff}(\theta) - \frac{\kappa_e F(\theta)}{c}\right)\right]^{\frac{\alpha'-1}{\alpha'}} F^{1/\alpha'}(\theta)$$

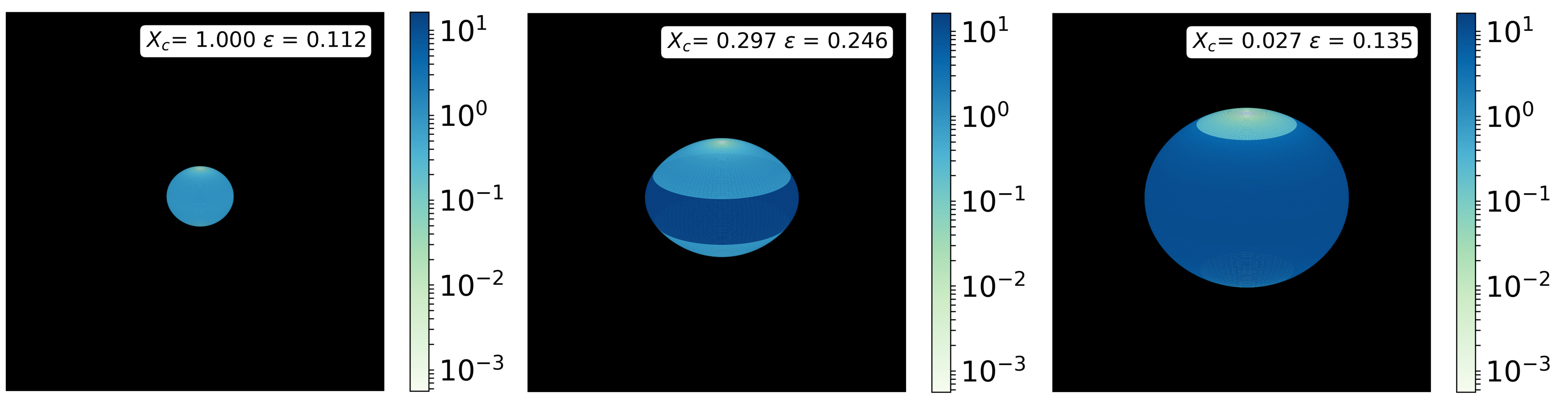
The parametrisation of the FMPs (α & k) accounts for the rotation-induced bi-stability jump at $T_{\rm eff}^{\rm jump} \simeq 22\ 500$K

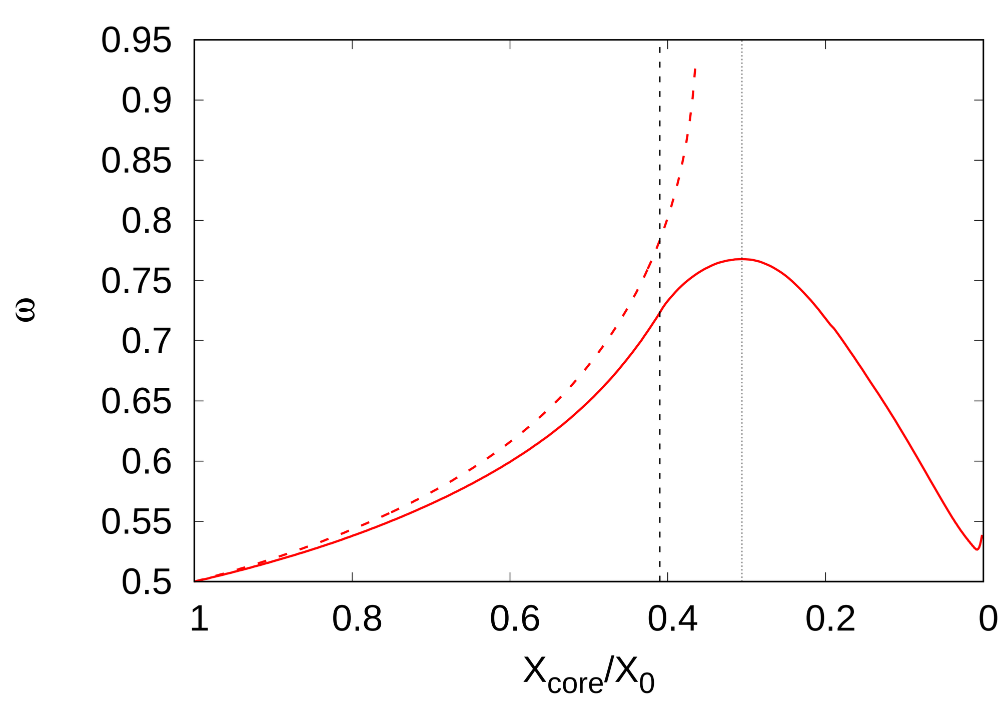


- Single Wind Regime (SWR) if $\nexists\theta_{\rm jump}$ where $T_{\rm eff}(\theta_{\rm jump}) = T_{\rm eff}^{\rm jump}$: mass-flux favored at the poles
- Two Winds Regime (TWR) if $\exists\theta_{\rm jump}$ where $T_{\rm eff}(\theta_{\rm jump}) = T_{\rm eff}^{\rm jump}$: mass-flux favored at the equator and global mass loss rate increased
- Mass-flux discontinuity at $\theta = \theta_{\rm jump}$

5. Main Sequence evolution

15 $M_\odot$ star initially rotating at 50% of critical rotation





- In the SWR, $\omega = \Omega_{\rm eq}/\Omega_k$ increases
- Stellar expansion makes $T_{\rm eff,eq}$ decrease to the point where the star enters a TWR

This is followed by two phases of evolution:

- Phase 1: Strong increase of the global mass/AM loss rates $\to \omega$ keeps increasing but slower
- Phase 2: AM loss sufficient for ω to decrease

In comparison, stars with negligible mass loss ($M < 7\ M_\odot$) have an increasing ω along the MS, because they become more and more centrally condensed.

6. Conclusions

- Radiative acceleration only mildly influences the critical angular velocity
- Discontinuity of $\dot{M}$–$T_{\rm eff} \longrightarrow 2$ wind regimes
- SWR: Mass loss favored at the poles
- TWR: Strong mass and AM loss around the equator
- AM extraction can prevent massive stars from reaching criticality
- Evolution of ω very dependent on ZAMS conditions (M & ω_i)
- Mass loss prescriptions are very uncertain
- Phenomenon involved in the evolution of rotation are non-linear