Main sequence evolution of rapidly rotating early-type stars

Journée des thèses

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IRAP

June 21st 2017

Introduction

- Rotation...
  - breaks the 1D spherical symmetry
  - is responsible for large scale mixing processes of chemical elements and angular momentum
- Typical 1D models : rotation $\equiv$ small perturbation
  - Justified for slow rotators (Zahn 1992)
- Early-type stars : often fast rotators
  - 2D evolution possible with the ESTER code
    (Espinosa Lara & Rieutord 2013 ; Rieutord et al. 2016)

Mass-loss via radiative winds

- Massive stars ($M > 7M_\odot$) have winds driven by radiation
- Continuum & line absorptions transfer radiation momentum to stellar matter
  - Matter acceleration outward
  - Mass & angular momentum loss
- At each step, we decrease the mass and the global angular momentum of the star

local mass-flux prescription

- Approximations (CAK 1975)
  - Radiative wind : isothermal & stationary flow
  - Star : point source of radiation
- Derivation based on Bard & Townsend 2016 method
- Only need mass and momentum conservation equations

local mass-flux prescription

After a mathematical derivation for $c_s << 1$:

$$\dot{m}(\theta) = \frac{\alpha}{1-\alpha}\left(\frac{\bar{Q}\Gamma_e(\theta)}{1-\Gamma_e(\theta)}\right)^{\frac{1-\alpha}{\alpha}} \frac{\sigma T_{\mathrm{eff}}(\theta)^4}{c^2}\Phi_R(\theta)$$

where

$$\Phi_R(\theta) = \left(1 - \frac{R(\theta)^3\Omega(\theta)^2 \sin\theta}{GM(1-\Gamma_e(\theta))}\right)^{-\frac{1-\alpha}{\alpha}}$$

is the rotation term and
α is the CAK index that we take as constant : $\alpha = 0.5$
$\bar{Q}$ is Gayley 1995 dimensionless line strength parameter ($\sim 2 \times 10^3$)

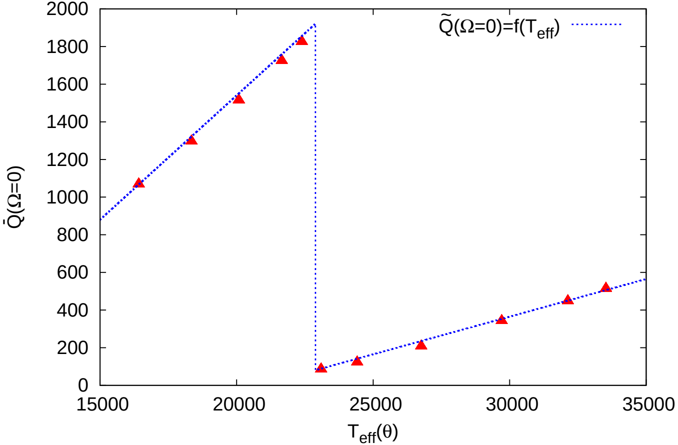
$\bar{Q}$ calibration and bi-stability jumps

- Vink et al. 1999 : recombination of Fe IV into Fe III around $T_{\text{eff}}^{\text{jump}} \simeq 25\ 000K \rightarrow \dot{M}$ increases by a factor $\sim 5 - 10$
- $\bar{Q} = cste$ ignores this phenomenon
- $\bar{Q}$ has to take the radiative acceleration jump into consideration around this temperature

$\longrightarrow$ $\bar{Q}$ is calibrated with Vink et al. 2001 prescription for mass-loss in the non-rotating limit ($\Phi_R = 1$)

$$\frac{\dot{M}_{\text{Vink}}}{4\pi R(\theta)^2} = \dot{m}(\theta, \Phi_R = 1)$$

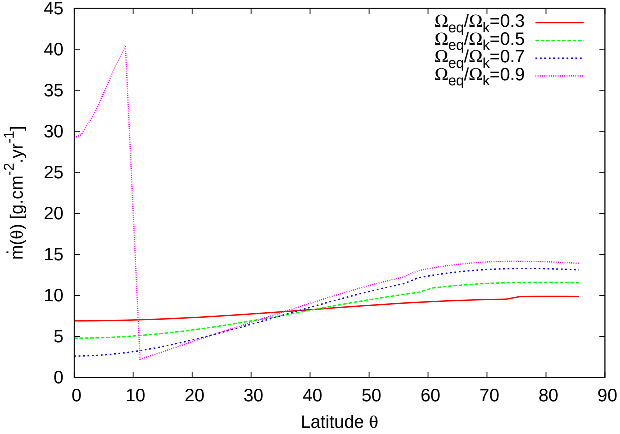
$\bar{Q}$ calibration and bi-stability jumps



$$\tilde{Q}(T_{\rm eff}) \simeq \begin{cases} 0.132 \times T_{\rm eff} - 1100, & \text{if } T_{\rm eff} \leq T_{\rm eff}^{\rm jump} \\ 0.04 \times T_{\rm eff} - 835, & \text{if } T_{\rm eff} > T_{\rm eff}^{\rm jump} \end{cases}$$

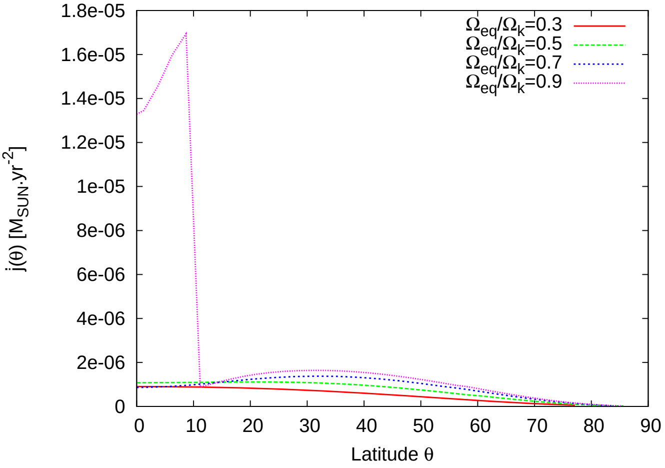
Local mass-flux

$M = 15 M_{\odot}$



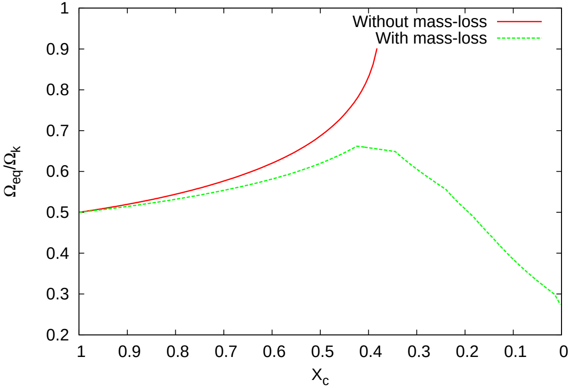
Strong mass-flux in the equatorial region → Be stars ?

$$\dot{j}(\theta) = \dot{m}(\theta)\Omega_{eq}(\theta)R^2(\theta)\sin^2\theta$$



$\frac{\Omega_{eq}}{\Omega_k}$ evolution

$$\Omega_k = \sqrt{GM/R_{eq}^3},\ M = 15M_\odot$$



Bi-stability jumps are of crucial interest regarding stellar evolution on the MS

Conclusion

- New mass-flux prescription accounting for bi-stability jumps via $\tilde{Q}$
- Rotation induced bi-stability :
  - Enhanced mass-flux for $\theta < \theta_{\rm jump}$
    $\longrightarrow$ Be stars disk ?
  - Enhanced global loss of angular momentum
    $\longrightarrow$ $\frac{\Omega_{eq}}{\Omega_k}$ drop

$\longrightarrow$ 2D models essential for rapidly rotating stars evolution