Main sequence evolution of rapidly rotating early-type stars

Journée des thèses

Damien Gagnier
Supervisors : Michel Rieutord & Corinne Charbonnel

IRAP

June 21st 2017
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)
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 $c_s << 1$:

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

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

$\alpha$ 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 
  \( T_{\text{eff}}^{\text{jump}} \approx 25000K \) \( \rightarrow \dot{M} \) increases by a factor \( \sim 5 - 10 \)

- \( \bar{Q} = \text{cste} \) ignores this phenomenon

- \( \bar{Q} \) has to take the radiative acceleration jump into consideration around this temperature

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

\[
\frac{\dot{M}_{\text{Vink}}}{4\pi R(\theta)^2} = \dot{m}(\theta, \Phi_R = 1)
\]
\[ \tilde{Q}(T_{\text{eff}}) \approx \begin{cases} 
0.132 \times T_{\text{eff}} - 1100, & \text{if } T_{\text{eff}} \leq T_{\text{jump}}^{\text{eff}} \\
0.04 \times T_{\text{eff}} - 835, & \text{if } T_{\text{eff}} > T_{\text{jump}}^{\text{eff}} 
\end{cases} \]
Local mass-flux

\[ M = 15M_\odot \]

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

\[ \dot{j}(\theta) = \dot{m}(\theta) \Omega_{eq}(\theta) R^2(\theta) \sin^2 \theta \]
\[ \frac{\Omega_{eq}}{\Omega_k} \text{ evolution} \]

\[ \Omega_k = \sqrt{\frac{GM}{R_{eq}^3}}, \ M = 15M_{\odot} \]

![Graph showing the \( \frac{\Omega_{eq}}{\Omega_k} \) evolution over the mass fraction \( \chi_c \). The graph includes two curves: one for without mass-loss and another for with mass-loss.]

**Bi-stability jumps are of crucial interest regarding stellar evolution on the MS**
New mass-flux prescription accounting for bi-stability jumps via $\tilde{\dot{Q}}$

Rotation induced bi-stability:

- Enhanced mass-flux for $\theta < \theta_{\text{jump}}$
  $\rightarrow$ Be stars disk?
- Enhanced global loss of angular momentum
  $\rightarrow$ $\frac{\Omega_{\text{eq}}}{\Omega_k}$ drop

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