Initial conditions of early type stars reaching critical rotation during the main sequence

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Introduction

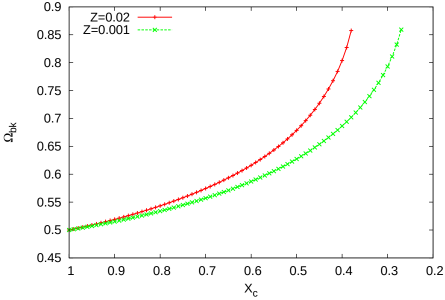
- Rotation breaks the 1D-imposed spherical symmetry
- Rotating stars : distorted by centrifugal acceleration & large scale flows
- Global rotational effects can be approximated in 1D codes (rotational mixing...) as advection-diffusion process (Geneva code) or purely diffusive process (MESA code).

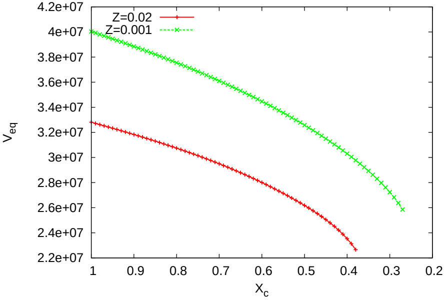
$\longrightarrow$ But only for slow rotator (Zahn 1992)

- Here we only look at early type stars : often fast rotators close to criticality and subject to mass-loss.
- Goal : looking at the initial conditions that permit critical rotation during the MS.

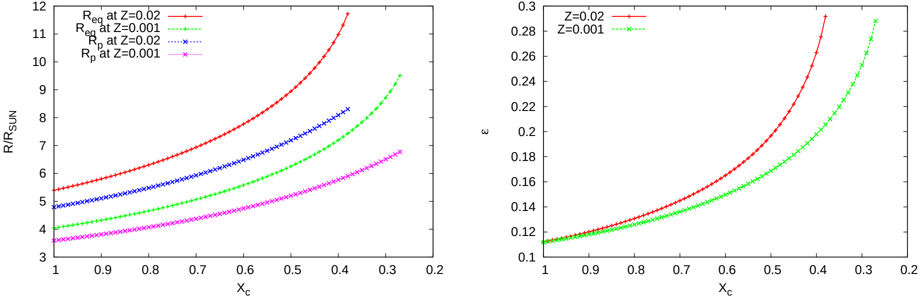
Evolution without angular momentum loss

- No mass-loss nor angular momentum loss
- Time-evolution mimicked by a decrease of X_c with ESTER
- $M = 15M_\odot$, $Z = 0.02$ & 0.001 initially rotating at 50% of the critical angular velocity.



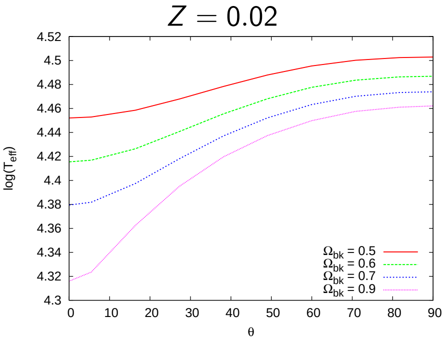


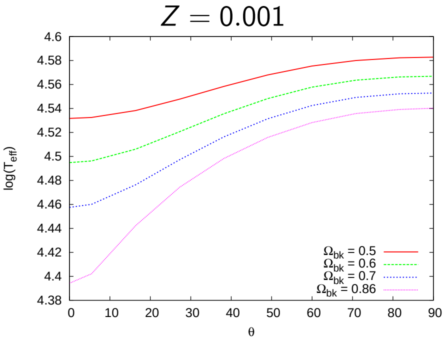
Evolution without angular momentum loss



- Star expands faster at the equator than at the pole
  - Centrifugal effect weakly affects the polar region but does affect the equator
  - R_{eq} increases $\rightarrow \Omega_k = \sqrt{\frac{GM}{R_{eq}^3}}$ decreases $\rightarrow \Omega_{bk} = \Omega_{eq}/\Omega_k$ increases
  - Flattening $\epsilon = 1 - R_p/R_{eq}$

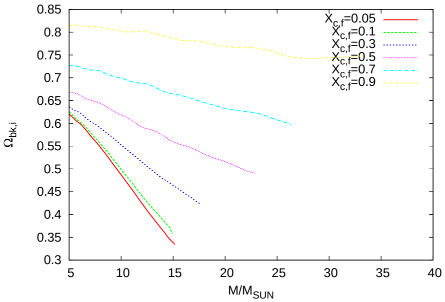
Evolution without angular momentum loss

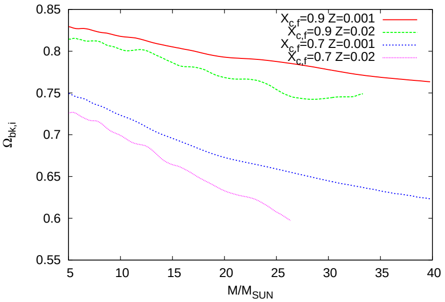




- Amplitude of T_{eff} greater for $Z = 0.001$
    - Smaller amount of heavy elements → less opaque star → photons can easily propagate through the star and heat the surface.

Evolution without angular momentum loss





- Transport of energy from core to surface through convective and radiative processes
  - Star warms up, becomes less dense and expands → Ω_k decreases
- The more massive the star, the smaller $\Omega_{bk,i}$ has to be
- The smaller $X_{c,f}$, the smaller $\Omega_{bk,i}$ has to be
- Decreased metallicity → decreased opacity → star more compact (Maeder 2009)

Evolution with angular momentum loss

- All hot stars have winds driven by radiation
- The main transfer of momentum is due to the absorption of the stellar radiation by stellar lines.
- At each X_c step, we also decrease the mass of the star according to Vink et al. (2001) prescription on mass-loss.

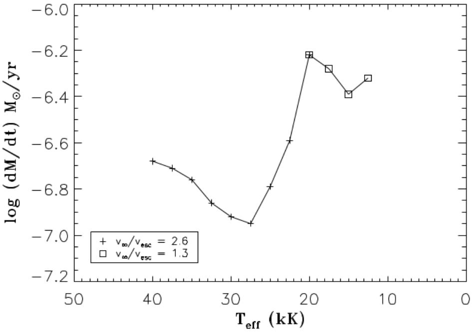
Evolution with angular momentum loss : Vink et al. 2001 prescription

$$\begin{aligned}\log \dot{M} = & -6.697(\pm 0.061) \\ & +2.194(\pm 0.021)\log(L_*/10^5) \\ & -1.313(\pm 0.046)\log(M_*/30) \\ & -1.226(\pm 0.037)\log\left(\frac{v_\infty/v_{esc}}{2.0}\right) \\ & +0.933(\pm 0.064)\log(T_{\rm eff}/40000) \\ & -10.92(\pm 0.90)\{\log(T_{\rm eff}/40000)\}^2 \\ & +0.85(\pm 0.10)\log(Z/Z_\odot)\end{aligned}$$

for $T_{\rm jump} < T_{\rm eff} \leq 50000K$

$$\begin{aligned}\log \dot{M} = & -6.688(\pm 0.080) \\ & +2.210(\pm 0.031)\log(L_*/10^5) \\ & -1.339(\pm 0.068)\log(M_*/30) \\ & -1.601(\pm 0.055)\log\left(\frac{v_\infty/v_{esc}}{2.0}\right) \\ & +1.07(\pm 0.10)\log(T_{\rm eff}/20000) \\ & +0.85(\pm 0.10)\log(Z/Z_\odot)\end{aligned}$$

for $12500K \leq T_{\rm eff} \leq T_{\rm jump}$



- Around $T_{\text{eff}} = 25000K$, $\dot{M}$ jumps due to the recombination of Fe IV into Fe III which has a stronger line acceleration below the sonic point.
- T_{jump} can be calculated.
- Other bi-stability jumps around $15000K$ and $35000K$.

(Vink et al. 1999)

Mass-loss and angular momentum loss

- We calculate the mass-loss rate at each X_c step.
- At each colatitude we assume a θ-dependant mass-loss rate and angular momentum loss rate
- Integration over the colatitude $\rightarrow$ total mass-loss and angular momentum loss at each step.

$$\Delta M = \iint \frac{\dot{M}(\theta)\delta t}{4\pi R^2(\theta)} dS \tag{1}$$

$$\Delta J = \iint \frac{\dot{M}(\theta)\delta t}{4\pi R^2(\theta)} \Omega(\theta) R^2(\theta) \sin^2\theta dS \tag{2}$$

where $\delta t = \delta X_c \mathrm{T}_{\mathsf{nucl}}$, the area at the stellar surface

$$dS = R^2(\theta)\sqrt{1 + \frac{R_\theta^2}{R^2(\theta)}} \sin\theta d\theta d\phi \qquad \mathrm{T}_{\mathsf{nucl}} = 10^{11}(M_*/M_\odot)(L_\odot/L_*)q_{c,*}$$

Mass-loss and angular momentum loss

- At each X_c-step :

$$\Delta M = \frac{1}{2} \int \dot{M}(\theta) \delta t \sqrt{1 + \frac{R_\theta^2}{R^2(\theta)}} \sin\theta d\theta \tag{3}$$

$$\Delta J = \frac{1}{2} \int \dot{M}(\theta) \Omega(\theta) R^2(\theta) \delta t \sqrt{1 + \frac{R_\theta^2}{R^2(\theta)}} \sin^3\theta d\theta \tag{4}$$

BUT we have to be sure that our time-step $\delta t = \delta X_c \mathrm{T}_{\mathrm{nucl}}$ is greater than the required time for the redistribution of angular momentum $\mathrm{T}_{ES} = \mathrm{T}_{KH} G M_* / \Omega^2 R_*^3$ ($\mathrm{T}_{KH} = G M_*^2 / R_* L_*$) !

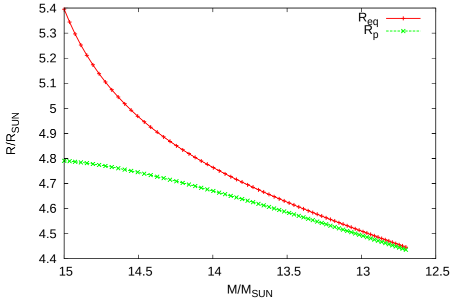
Evolution with angular momentum loss : timescales

$M_*/M_\odot$	Ω_{bk}	T_{ES} (yrs)	$\mathrm{T}_{\mathrm{nucl}}$ (yrs)
10	0.5	$3 \cdot 10^5$	$5.73 \cdot 10^7$
10	0.8	$1.59 \cdot 10^5$	$5.85 \cdot 10^7$
20	0.5	$1.9 \cdot 10^5$	$2.10 \cdot 10^7$
20	0.8	$1.9 \cdot 10^5$	$2.14 \cdot 10^7$
30	0.5	$9.5 \cdot 10^4$	$1.39 \cdot 10^7$
30	0.8	$3.17 \cdot 10^4$	$1.41 \cdot 10^7$

$\longrightarrow \delta X_{c,min} \simeq 0.01$

Mass-loss without nuclear evolution of the star

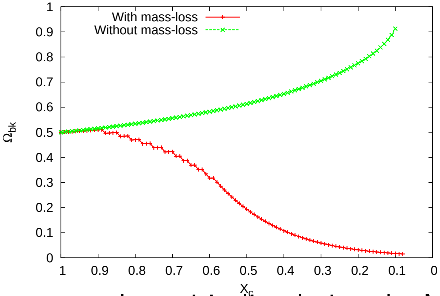
- Will a star contract or expand if we extract mass without nuclear evolution ?
  - Fully convective stars : well represented by $n = 1.5$ polytrope $\rightarrow$ the remaining mass expands (Chandrasekhar 1967).
  - $M = 15\ M_\odot$ star rotating with $\Omega_{bk} = 0.5$



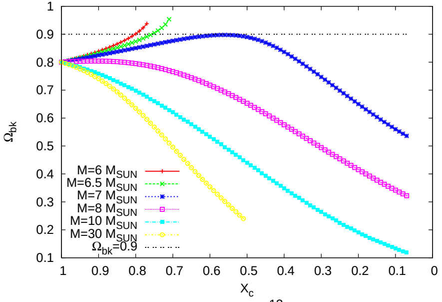
  - The star contacts following its mass-loss in analogy with polytropic radiative stars ($n \simeq 3$ and $\gamma \simeq 5/3$) Heisler & Alcock 1986.

Evolution with angular momentum loss

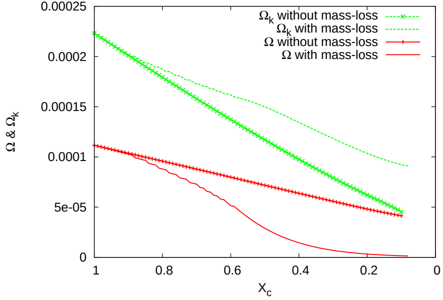
- The evolution of Ω_{bk} during the main sequence depends on both the contribution of the loss of angular momentum and of the nuclear reactions.
- $M = 10\ M_{\odot}$ initially rotating at 50% of the critical angular velocity.



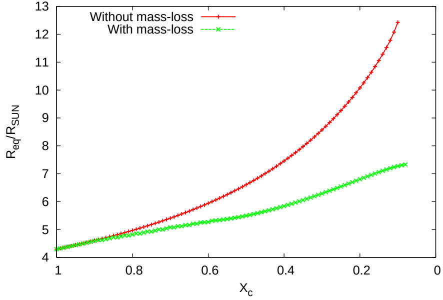
- No mass-loss : star reaches criticality during the MS
- Mass-loss : it doesn't but two regimes :
  - $X_c > 0.9$: Ω_{bk} slightly increases : Nuclear contribution 'wins'
  - $X_c < 0.9$: Ω_{bk} decreases : angular velocity decreases faster than Ω_k decreases.



Ω_{bk}
X_c
M=6 M_{SUN}
M=6.5 M_{SUN}
M=7 M_{SUN}
M=8 M_{SUN}
M=10 M_{SUN}
M=30 M_{SUN}
Ω_{bk}=0.9



Ω & Ω_k
X_c
Ω_k without mass-loss
Ω_k with mass-loss
Ω without mass-loss
Ω with mass-loss



R_{eq}/R_{SUN}
X_c
Without mass-loss
With mass-loss