

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



Damien Gagnier

Supervisors : Michel Rieutord & Corinne Charbonnel

Institut de Recherche en Astrophysique et Planétologie

damien.gagnier@irap.omp.eu

1. Introduction

Among the numerous problems that one faces when modelling stars, those related to rotation are of particular nature, in the frame of typical 1D models, since rotation breaks the imposed spherical symmetry. Rotating stars are not only distorted by the centrifugal acceleration, but they are also pervaded by large-scale flows that carry chemical elements and angular momentum. The importance of these effects has been appreciated for quite some time now [e.g. 6], and a specific modelling is now included in 1D stellar evolution codes to reproduce the expected effects of global rotation. Studying rapidly rotating stars with 1D models is however hazardous regarding the approximations used. The achievement of the first self-consistent 2D models, worked out by Espinosa Lara and Rieutord [e.g. 4, 8], fortunately opens the door to the exploration of the evolution of such fast rotators.



Figure 1: Gravity darkening (i.e. surface gravity gradient from equator to pole) for an intermediate mass star rotating at 90% of the critical angular velocity.

In this paper we present a first 2D investigation of the history of stars rotating close to criticality when subject to radiation driven winds. For that we use the ESTER stellar models [8], and we look at their evolution throughout the main sequence (MS).

2. Method

All hot stars are subject to winds driven by radiation, in this work, we will therefore consider the effects of those winds on the outer layers of stars. To do that, we evolve the star through the MS by decrementing the fractional abundance of hydrogen in the convective core X_c at each time-step via a simple scheme for hydrogen burning. At each step, we also decrease the mass of the star using an adapted version of [1] local surface mass-flux prescription for rotating stars which can be seen as a local equivalent of the usual mass-loss rate from [2]. The goal is then to see whether a star will reach critical rotation during the MS depending on its initial conditions.

3. Local surface mass-flux prescription

In order to keep the physical model as simple as possible, we assume the radiative wind to be an isothermal stationary flow that is driven outward through absorption, assuming that the star is a point source of radiation. Following [1] and [2], we end up with a local mass-flux prescription

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

where

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

is the term associated with rotation. α is the CAK power index that will be taken at $\alpha = 0.5$, $\bar{Q}$ is the dimensionless line strength parameter from [5] which he said to be of order 10^3 , and $\Gamma_e = \kappa_e L / (4\pi c G M)$ is the Eddington parameter. [10] calculations for wind models for OB stars show that around $T_{\text{eff}} = 25\,000\text{K}$, the mass-loss rate $\dot{M}$ jumps due to the recombination of Fe IV into Fe III which has a stronger line acceleration below the sonic point. This phenomenon

is called a bi-stability jump and prevents $\bar{Q}$ from being taken as constant. Using [11] to calibrate $\bar{Q}$, one finds

$$\bar{Q}(T_{\text{eff}}) \simeq \begin{cases} 0.132 \times T_{\text{eff}} - 1050, & \text{if } T_{\text{eff}} \leq T_{\text{eff}}^{\text{jump}} \\ 0.04 \times T_{\text{eff}} - 835, & \text{if } T_{\text{eff}} > T_{\text{eff}}^{\text{jump}} \end{cases} \quad (3)$$

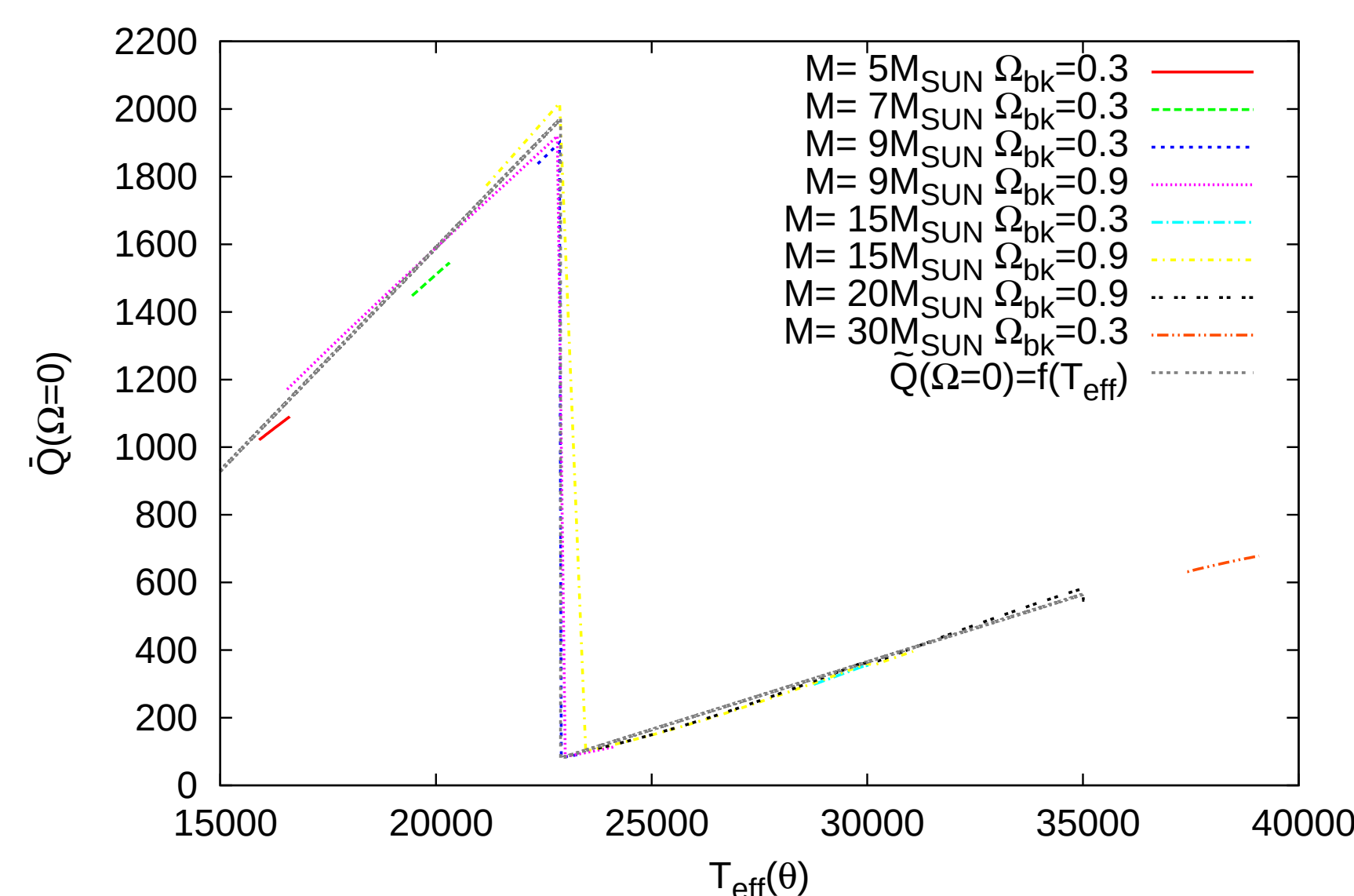


Figure 2: Dimensionless line strength parameter $\bar{Q}$ as a function of the effective temperature T_{eff} for various masses and angular velocity ratio Ω_{bk} when rotation is neglected ($\Phi_R = 1$).

4. Results & Discussion

Let's now look at the variation of $\dot{m}(\theta)$ with the latitude θ , as well as the variation of the associated angular momentum flux

$$\dot{j}(\theta) = \dot{m}(\theta) \Omega(\theta) R(\theta)^2 \sin^2 \theta. \quad (4)$$

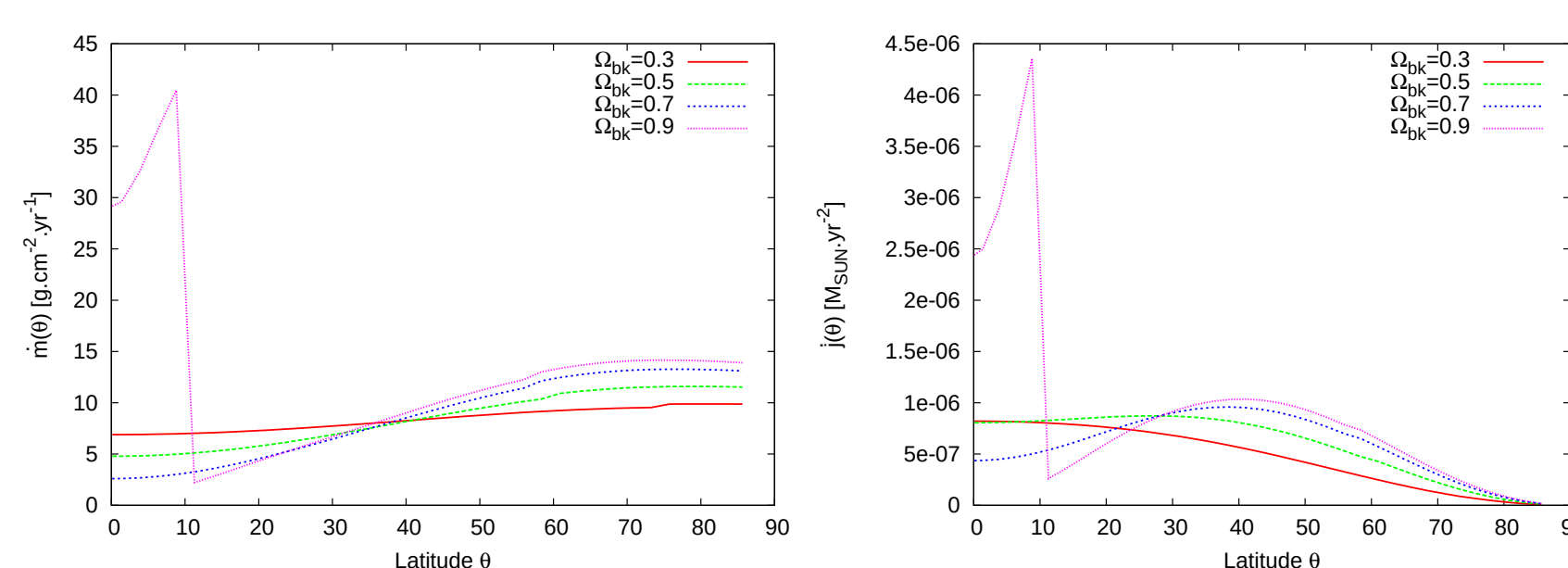


Figure 3: Variation of the mass flux and angular momentum flux as a function of latitude for a $M = 15M_{\odot}$ star at $Z = 0.02$ and various Ω_{bk} .

- In "standard" cases, most angular momentum (and mass) is lost at intermediate latitude regions.
- In case of rotation-induced bi-stability jump (e.g. $\Omega_{bk} = 0.9$ figure 3), the global loss of angular momentum (and mass) is increased and is highly dominated by the equatorial region contribution. We could therefore expect a spin-down of bi-stable stars during the MS.

Figure 4 shows the MS evolution of the angular velocity at the equator in units of the critical velocity Ω_{bk} as a function of the fractional abundance of hydrogen in the convective core X_c for multiple masses with a ZAMS angular velocity $\Omega_{bk,i} = 0.7$.

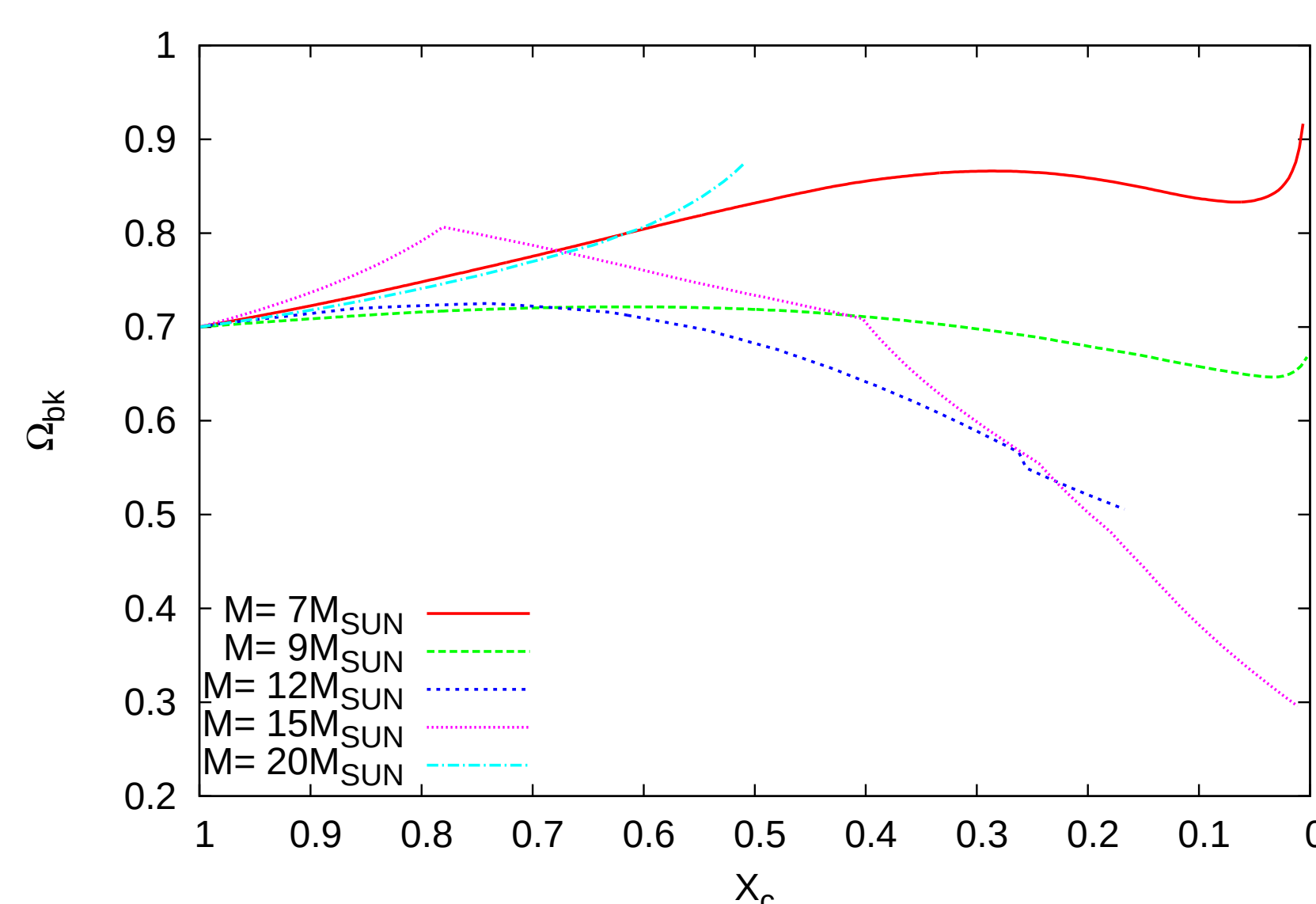


Figure 4: Angular velocity at the equator in units of the critical velocity Ω_{bk} as a function of the fractional abundance of X_c . $Z = 0.02$.

It is clear that depending on the initial mass of the star, the evolution of Ω_{bk} will be very different.

- $M < 7M_{\odot}$ stars have very weak radiative winds, and are not bi-stable. They will most-likely reach criticality during the MS. The fate of more massive stars is a bit more complicated.
- $7M_{\odot} \leq M < 9M_{\odot}$ stars become bi-stable during their MS evolution greatly increasing the global angular momentum loss and inducing a decrease of Ω_{bk} . Once Ω_{bk} has decreased enough, the star becomes non bi-stable again.
- $9M_{\odot} \leq M < 15M_{\odot}$ stars begin their evolution being bi-stable with a very small θ_{jump} . Their global loss of angular momentum remains quite low. As Ω_{bk} increases, θ_{jump} migrates towards the pole leading to a stronger and stronger loss of angular momentum up to the point where Ω_{bk} starts decreasing and eventually becomes non-bistable again.
- $15M_{\odot} \leq M \leq 20M_{\odot}$ stars are not bi-stable at the beginning of the MS but are subject to stronger radiative winds. As Ω_{bk} increases, they may become bi-stable before reaching criticality leading to an eventual decrease of Ω_{bk} .

For a given initial angular velocity ratio $\Omega_{bk,i}$, it is therefore not quite obvious whether a more or less massive star will reach criticality, mostly due to the existence or not of bi-stability jumps. However, in order to reach criticality, stars must already be rapidly rotating at ZAMS.

5. Conclusion

Now that we have some ideas of the initial conditions of stars reaching critical rotation during the MS, some consequences of their evolution need to be explored. In particular, when critical rotation is reached, a new way of losing mass through mechanical mass-loss is given to a star, what are its effects? How does the angular momentum redistribute in stellar interiors during the MS evolution? And what are the effects of mass ejection on the interstellar medium? All those questions remain to be answered in future works.

References

- [1] Bard, C. & Townsend, R. H. D. 2016, , 462, 3672
- [2] Castor, J. I., Abbott, D. C., & Klein, R. I. 1975, , 195, 157
- [3] Charbonnel, C., Chantereau, W., Krause, M., Primas, F., & Wang, Y. 2014, A&A, 569, L6
- [4] Espinosa Lara, F. & Rieutord, M. 2013, A&A, 552, A35
- [5] Gayley, K. G. 1995, , 454, 410
- [6] Maeder, A. & Meynet, G. 2000, Ann. Rev. Astron. Astrophys., 38, 143
- [7] Owocki, S. P., Castor, J. I., & Rybicki, G. B. 1988, , 335, 914
- [8] Rieutord, M., Espinosa Lara, F., & Putigny, B. 2016, J. Comp. Phys., 318, 277
- [9] Townsend, R. H. D., Owocki, S. P., & Ud-Doula, A. 2007, , 382, 139
- [10] Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 1999, , 350, 181
- [11] Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2001, A&A, 369, 574