Part 2

Interiors of Massive Stars

André Maeder telling Stan Owocki to do something about it

A Massive Star Odyssey, from Main Sequence to Supernova
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The role of rotation and mass loss in the evolution of massive stars

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Abstract. Rotation affects all the outputs of the evolution and nucleosynthesis of massive stars. We discuss the evolution of the rotational velocities, the internal Ω-gradients, the tracks in the H-R diagram, the age determinations, the evolution of the surface N/C abundance ratios, the B/R number ratios of blue to red supergiants and the lifetimes in the WR stages.

1. Introduction

Mass loss plays an essential role in massive star evolution (Chiosi & Maeder 1986; Maeder & Conti 1994). The mass loss rates depend on metallicity Z and therefore Z influences very much the lifetimes and properties of the stars in the post-MS stages, such as the LBV, the blue- and red-supergiants and the WR stars, as well as the chemical abundances and the yields.

Over recent years, it has appeared that rotation may also be important in massive star evolution (Maeder & Meynet 2000a) and affect the various model outputs (Meynet & Maeder 2000; Heger & Langer 2000; Heger *et al.* 2000). Here, we show some recent results about rotation in massive stars.

2. Brief note on the model physics

Several aspects of the physics of models with rotation were discussed in a series of papers I - IX by Maeder and Meynet (1997 - 2002); they concern:
(*i*) The structural equations for stars with differential rotation, the surface distorsions and the definition of $T_{\rm eff}$.
(*ii*) The processes of mixing and transport by meridional circulation and shear instabilities. In particular, new equations for properly accounting the effects of μ-gradients on the circulation have been written (Maeder & Zahn 1998).
(*iii*) The effects of rotation on the Eddington factor Γ and on the mass loss rates have been studied by Maeder & Meynet (2000b). The Eddington factor on the surface of a rotating star must be properly defined as a *local* ratio of the *local* flux to the *local* limiting flux. The maximum possible luminosity is reduced by rotation. Also, the critical break-up velocity $v_{\rm crit}$ is not defined by $v^2_{\rm crit} = \frac{GM}{r}(1-\Gamma)$ as often found in literature. This expression is incorrect, because it ignores the fact that the brightness varies on the surface of a rotating star. The appropriate expressions were derived by Maeder & Meynet (2000b).

The mass loss rates are enhanced by rotation. Two effects intervene, one is the higher $T_{\rm eff}$ at the pole which favours polar ejection ($g_{\rm eff}$-effect), the other one

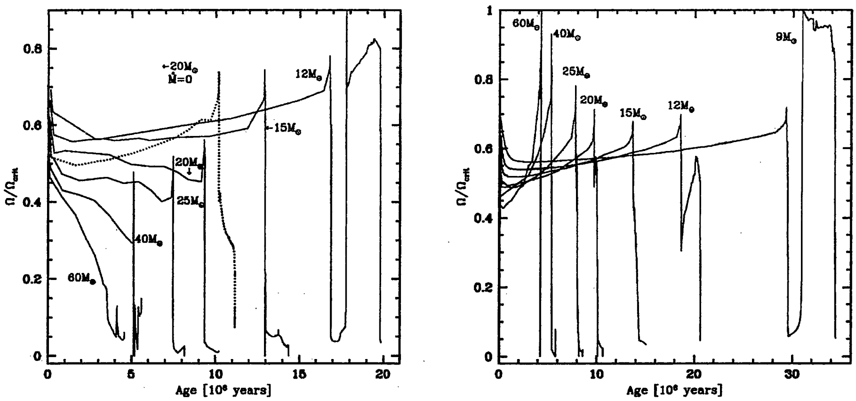

Figure 1. Evolution of the ratio $\Omega/\Omega_{\rm crit}$ of the angular velocity to the critical velocity at the surface of stars of different initial masses for a metallicity $Z=0.02$ (*left*) and $Z=0.004$ (*right*).

is the possibility that the opacity becomes higher at the equator, which is cooler, and this may enhance the equatorial mass loss (κ-effect). All accounted for, the ratio of the global mass loss rates for a rotating star to that of a non-rotating star at the same location in the H-R diagram is (Maeder & Meynet 2000b)

$$\frac{\dot{M}(\Omega)}{\dot{M}(0)} = \frac{(1-\Gamma)^{\frac{1}{\alpha}-1}}{\left[1-\frac{4}{9}\left(\frac{v}{v_{\rm crit}}\right)^2-\Gamma\right]^{\frac{1}{\alpha}-1}}, \qquad (1)$$

with $v_{\rm crit} = \left(\frac{2}{3}\frac{GM}{R_{\rm pb}}\right)^{\frac{1}{2}}$, where $R_{\rm pb}$ is the polar radius at break-up and α is a force multiplier, which for massive OB stars of Pop. I can be taken equal to ~ 0.6 (*cf.* Kudritzki, these Proceedings). For a hot star far from the Eddington limit, the maximum value of this ratio is about 1.5, while for stars close to the Eddington limit, this ratio may be much higher. Some consequences of the anisotropies of the mass loss rates will be discussed in Section 5 below.

3. H-R diagram, lifetimes and rotational velocities

During MS evolution, the angular velocities decrease in stellar interiors as a result of the transport and removal of angular momentum by mass loss. A gradient of $\Omega(r)$ appears in the stellar interior. Interestingly enough, this internal gradient is higher for models of lower metallicity Z, because there the transport by meridional circulation in the outer layers is much weaker. The physical reason is that the stellar density is higher in lower Z models, so that the Gratton-Öpik term in $\frac{\Omega^2}{2\pi G \rho_{\rm m}}$ which contributes to outwards transport is much smaller, ($\rho_{\rm m}$ is the average density interior to the level considered, *cf.* Maeder & Zahn 1998). These higher internal Ω-gradients at lower Z will favour mixing by shear instabilities. We recall that shears are the most efficient mechanisms for the

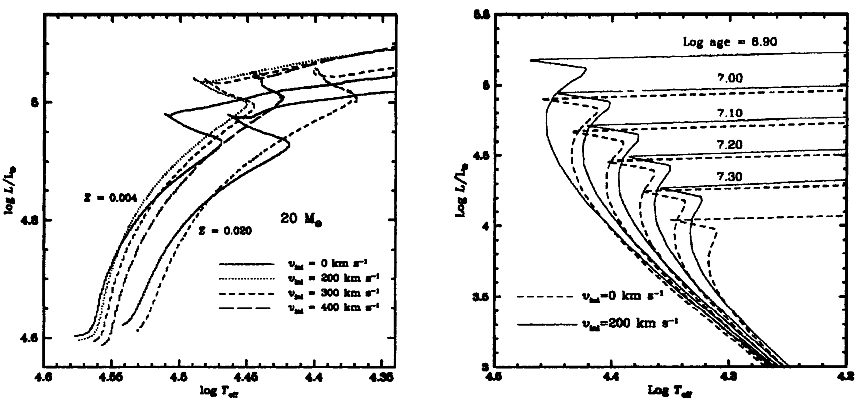

Figure 2. *Left:* Evolutionary tracks for 20 $M_\odot$ models with different velocities and Z. *Right:* Isochrones for $Z=0.02$. The dashed line represent non-rotating models, the continuous line represents models with an initial rotation of 200 km s^{-1}. The log(age) are indicated for models with rotation. The isochrones with rotation correspond to those without rotation with an age lower by 0.1 dex. This means that the account for rotation leads to ages 25% larger.

transport of chemical elements, while meridional circulation mainly transports the angular momentum (*cf.* Meynet & Maeder 2000).

Figure 1 shows the evolution of the ratio of the angular velocity to the critical velocity at the stellar surface as a function of the stellar masses for models with $Z=0.02$ and 0.004. At $Z=0.02$, we notice a fast decrease of rotation during the MS phase for stars with masses above 15 $M_\odot$, while below this mass the velocities stay around 200 km s^{-1} up to the end of the MS phase. At $Z=0.004$, the behaviour is very different. The strong decrease is absent because the removal of angular momentum by mass loss is much smaller. The most massive stars even tend to easily reach break-up. This shows how much the evolution of rotation depends on the mass loss rates. Here, isotropic mass loss rates are supposed, but the account for anisotropies may change this behaviour. Enhanced polar mass loss as it is likely to occur for the most massive stars will lead to a smaller decrease of rotation, while enhanced equatorial mass loss, as likely for B-type stars, will lead to a faster decrease. Also, if there is any magnetic coupling, the decrease may be faster.

Thus, we see that paradoxically the lower mass loss rates at lower Z may lead to break-up, and thus to high mass loss in the course of MS evolution. The consequences for $Z=0$ models needs to be examined carefully. In this connexion, it appears that clusters at lower Z have more Be stars (*cf.* Maeder *et al.* 1999), *i.e.*, stars close to break-up. At present, we do not know whether this is just the consequence of the above effect or whether the initial rotation velocities are also higher at lower Z.

Figure 2 (left) shows the effects of rotation on the 20 $M_\odot$ track. We see that these effects mimic those of overshooting. This is well expected since rotation enlarges the convective core and creates a mild internal gradient just outside

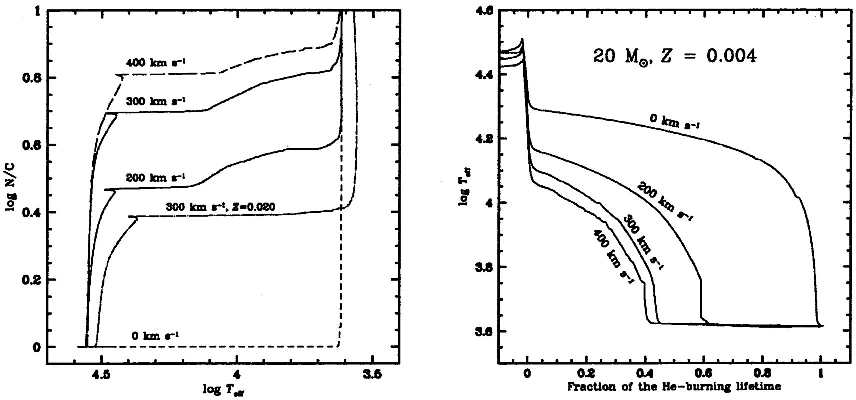

Figure 3. *Left*: Evolution of N/C, the nitrogen to carbon ratio in mass fraction, as a function of $T_{\rm eff}$ for 20 M$_\odot$ models. The abundances are normalized to their initial values. The models are for $Z = 0.004$ for different initial velocities. The case of 20 M$_\odot$ at $Z = 0.02$ with an initial rotation of 300 km s^{-1} is also indicated. *Right:* Evolution of $T_{\rm eff}$ as a function of the fraction of the lifetime spent in the He-burning phase for different rotation velocities.

the core. This means that the importance of overshooting is likely smaller than usually assumed. We suggest a value of 0.1 H_p for the distance of overshooting. At solar metallicity, the MS lifetimes are also increased by rotation, typically by 20 to 30 % for the average rotation. As shown by Figure 2 (right), when rotation is accounted for, the ages determined are typically 25 % higher than if we ignore rotation. As suggested by R. Rebolo (private comm.), this may reconcile the ages for the Pleiades determined from the turnoff of the upper MS with the ages determined from the lithium depletion in low mass stars (Martín *et al.* 1998).

4. Chemical abundances in Main Sequence and supergiant stars

Spectroscopic observations have shown that the fast rotators among OB stars always show N/C excesses (Herrero *et al.* 2000). Also observations of B- and A-type supergiants reveal a range of N/H excesses, which cannot be accounted for by dredge-up processes (Venn 1998, 1999). Figure 3 shows the predicted values of N/C. Firstly for $v = 0$, there is no increase after the MS phase. For an average rotation of $\sim$240 km s^{-1} (corresponding to an initial velocity of 300 km s^{-1}), at $Z = 0.02$ there is an increase of N/C by a factor of about 2.5, while at $Z = 0.004$ the increase is much higher and reaches a factor of about 5. Interestingly enough, these values well correspond to the observed N/C excesses for supergiants in the Milky Way and in the SMC. Physically, the reason for the higher N/C excesses at lower Z is due to the steeper internal Ω-gradients in lower Z models and to the smaller radii of these models, as discussed in Section 3.

5. The B/R number ratio problem

For two decades there was a lingering problem with the B/R number ratio of blue to red supergiants in galaxies. The observations show that there are

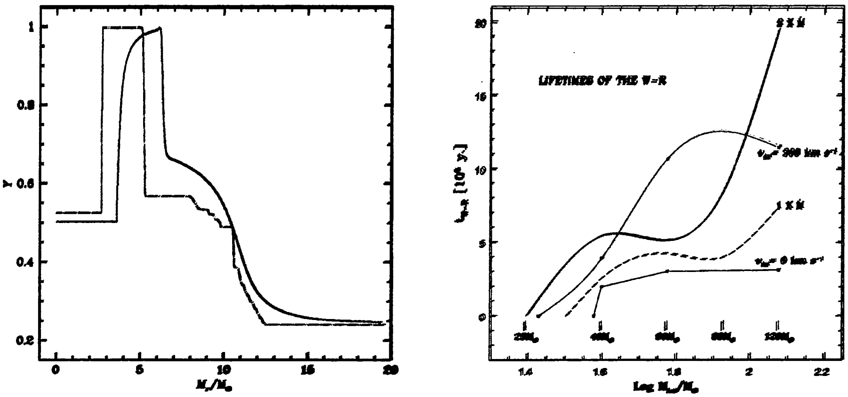

Figure 4. *Left:* Distribution of helium in two models of 20 $M_\odot$ at the middle of the He-burning phase with no rotation (broken line) and with an initial velocity of 300 km s^{-1}). The H-shell is just on the right of the He-peak. *Right:* Lifetimes in the WR stage for different models (see text).

lots of red supergiants at low Z as in the SMC (*cf.* Meylan & Maeder 1982; Humphreys & McElroy 1984). However, there was no model correctly predicting the above decrease of B/R with decreasing Z (see ref. in Langer & Maeder 1995). Rotation with the current assumptions described above appears to be able to solve this problem elegantly. Figure 3 (right) shows the evolution of $T_{\rm eff}$ during the He-burning phase of a 20 $M_\odot$ model with the SMC composition for different velocities. For $v = 0$, we see that most of the He-burning phase is spent in the blue, in agreement with current models, including our past ones. However, for models with a higher rotation, we see that a growing fraction of the He-burning phase is spent in the red. Indeed, for an average velocity of about 240 km s^{-1} on the MS, we see that a fraction 0.5-0.6 of the He-burning phase is spent in the red, which is in agreement with what is observed in the SMC.

The physical reason for this behaviour is illustrated in Figure 4 (left). The rotational mixing produces a larger He-core and also leads to more He diffused in the layers surrounding the He-core. Thus, during the He-burning phase, there is also more He in the H-burning shell, which is thus less active. In addition, the higher He-content makes the opacity lower. These two effects do not favour the presence of an intermediate convective zone. As is well known, convection implies a polytropic index $n = 1.5$, meaning a small internal density contrast and therefore a blue location in the H-R diagram.

6. Rotation and Wolf-Rayet stars

It is likely that most WR stars have a low rotation velocity as a result of heavy mass loss in previous stages. Nevertheless, rotation in OB stars strongly influences the formation and lifetimes of WR stars. As shown by Figure 4 (right), the two sets of models with only mass loss (*cf.* Meynet *et al.* 1994) show an increase of the lifetimes in the WR stage as a function of the initial mass and mass loss, (the set labelled '1×$\dot{M}$' was made with the current (high) rates at that time,

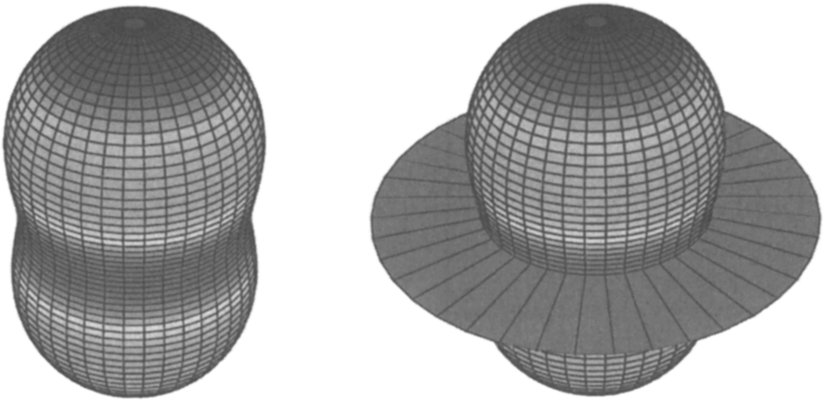

Figure 5. *Left:* Iso-mass loss distribution for a star with $\log \frac{L}{L_\odot} = 6.0$ and $T_{\rm eff} = 30\,000$ K with a fraction of break-up velocity equal to 0.80. *Right:* The same for the same model but with $T_{\rm eff} = 25\,000$ K.

the set with '$2\times\dot{M}$' is made with twice larger mass loss rates). This last set was in agreement with observed numbers of WR stars found in galaxies, (*cf.* Massey & Johnson 1998). Recently the O-type star mass loss rates have been estimated to be much lower (*cf.* Vink *et al.* 2000), consistently with the account of the clumping effect in the wind. The WR lifetimes for these mass loss rates and for zero rotation are shown in Figure 4 (right). They are much too small to account for the observed numbers of WR stars. Thus without rotation, we would have a major problem. However, for an initial velocity of 300 $\mathrm{km\,s^{-1}}$ corresponding to an average velocity of 240 $\mathrm{km\,s^{-1}}$ during the MS phase, we obtain much larger lifetimes in the WR stages, comparable to what was obtained with the old mass loss rates enhanced by a factor of 2. This is mainly the consequence of the rotational mixing which produces the bare core stage at an earlier phase of internal evolution.

Rotation also changes the balance between the WN and WC phases, in the sense that the very extended internal zone where H and He are mixed brings about a significant extension of the WN phase, while there is a more modest increase of the WC phase. Let us point out that rotation also leads to lower C/He, O/He and O/C abundance ratios in the WC phase, because the products are revealed at the surface at a slightly earlier stage of internal nuclear processing.

7. Conclusions and future developments

On the whole, we can say that rotation affects all the outputs of stellar evolution: tracks, lifetimes, star populations of blue, red supegiants, WR stars, as well as the surface composition, the chemical yields and the final stages, *etc.* ..

Future developments will include the effects of the anisotropies of the stellar winds as discussed by Maeder & Meynet (2000) and by Maeder & Desjacques (2001). As shown by Figure 5 (left), the distribution of mass loss for a rotating star with a high enough T_{eff} (so that the opacity is everywhere due to electron scattering) shows a characteristic peanut shape, while if the equatorial region becomes cooler than a bistability limit (21 500 K), the higher opacity in the equatorial regions favours equatorial mass loss (Figure 5 right). In the first case, the mass loss removes little angular momentum, while in the second case it removes a lot. Other effects, as the physics of the horizontal turbulence, the dynamical shears and the possible role of magnetic field are of great interest and will be studied in further works to provide the best possible grids of models.

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Discussion

KUDRITZKI: I agree entirely with you that measuring accurately the rotational velocities of very many massive stars during their evolution is an important program for the future. However, it is important not just to measure line widths and then to deduce v_{rot}, but to do careful profile fits in order to disentangle rotation from macroturbulence. Macroturbulence is clearly visible in high-resolution high S/N spectra and should not be forgotten about. It might be an important additional mixing mechanism.

MAEDER: I fully agree with you. We may wonder to what extent the observed macroturbulence is corresponding to the horizontal turbulence considered in rotating models. Also a very questionable point is the way the observational $v \sin i$ are presently determined.

NOMOTO: Is it possible to explain the red-blue evolution of the progenotor of SN 1987A by tuning the rotation parameter? What is your thought about the reason of the blueward evolution?

MAEDER: According to the value of the rotational velocity in the models with an initial mass of $\sim 20\,M_{\odot}$, the tracks show quite a variety of behaviour, including blue loops. However, for now we do not have yet made any full exploration of this problem.

HERRERO: You stated on Sunday that we should expect a small mass discrepancy because stars rotate. Looking at the diagrams I would say that the effect should be moderate. Do you think it is below the error bars of the spectroscopic mass determinations, which are about 20% of the stellar mass?

MAEDER: I do not think the mass discrepancy would be bigger than the factor you are giving. Indeed, the basic point is, 'a discrepancy with respect to what?' And as you well know, the rotating stars may have enlarged convective cores and milder chemical gradients, thus, they are more luminous that non-rotating stars of the same mass. This is the 'mass discrepancy' I was referring to.

EL EID: Does the main effect of rotation occur during the main sequence evolution?

MAEDER: Yes, but there may be also an influence of rotation on the helium burning or later phases of the pre-supernova evolution.

LEITHERER: What are final masses of the WR stars? Since the mass-loss rates are lower, they should be larger with the new models.

MAEDER: We used the recent O-type star mass loss rates by Vink *et al.* and we considered them corresponding to the average over the distribution of the rotational velocities. Then, depending on rotation the mass loss rates applied in the models may be larger or lower than the Vink *et al.* rates. When we apply this recipe together with mixing effects and Nugis & Lamers mass loss rates for WR stars, then we are obtaining relatively low final masses for WR stars (of the order of $10\,M_{\odot}$).

MOFFAT: On Sunday during the morning special session, I pointed out a potential Achilles' heal cluster in our Galaxy, NGC 7419, which contains a high fraction of RSGs (zero BSGs) and Be stars, much like clusters in the SMC. Does this simply mean that we are seeing a cluster whose initial rotation was much larger than average in the Galaxy, or does this pose a challenge to the rotation hypothesis?

MAEDER: NGC 7419 is not the only case, $h+\chi$ Persei also has a lot of RSGs, and many Be stars as well. I think that at a galactic metallicity it is much easier to form RSGs (the models show it). In addition, the fact that NGC 7419 has a lot of Be stars suggests that rotation is important in this cluster and, as we have shown, rotation helps a lot in suppressing the intermediate convective zone. Thus, I suspect that a close analysis of NGC 7419 may well support our models.