Mass Loss from Stars and the Evolution of Stellar Clusters
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Mass Loss and the Evolution of Massive Stars

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Abstract. Mass loss is a dominant effect of massive star evolution and together with rotation it has a deep impact on the evolution of star clusters. Mass loss influences the age estimates, the CNO abundances at the stellar surface, the properties of Be, B[e], LBV and WR stars, the supernova progenitors, the rotation properties of pulsars, the chemical yields and the spectral evolution of galaxies.

We first examine how mass loss behaves as a function of mass in comparison with internal mixing. The asymmetries of the mass loss by stellar winds in rotating stars influence the loss of angular momentum, a question of importance regarding the occurrence of GRBs. Rotation also globally enhances the mass loss rates. We discuss the filiations between the various kinds of massive stars, the effects of mass loss on the rotation velocities, on the changes of chemical abundances and on the chemical yields. A big issue concerns the stellar winds at low metallicity Z. Amazingly, if massive stars lose little mass by stellar winds, they reach critical rotation and experience a high rotational mass loss. We show that the CNO, Mg, Al anomalies observed in the most metal deficient stars of the galactic halo, as well as the He–rich stars in the globular cluster ω Cen, remarkably correspond to enrichments by rotational mass loss, which seems to play a great role in the early galactic evolution.

1. Personal Note

We are all very indebted to Henny Lamers for his major role in promoting the study of mass loss in stellar evolution. Around 1977, he convinced many of us about the importance of mass loss. We are still very grateful to him for the persuasion skills he developed at this occasion... At each step in the history of mass loss studies over the last 30 years, we see the major role of Henny for finding new ideas, developing them in a clever and efficient way, with a remarkable capacity to establish connexions between different subjects. Sometimes, it is said "if you have only one idea, keep it to yourself". But Henny has so many ideas and interests, that he needs not keep them to himself and shares his ideas, always having a lot of fun in doing it.

This great astrophysicist has played and will continue to play a great role in our science. We express to this good friend our personal gratitude for an always stimulating and fruitful interaction. Go ahead, Henny!

2. Mass Loss in Relation with Other Effects

Mass loss strongly influences all the model results of massive stars. The mass loss rates $\dot{M}$ for massive Main–Sequence stars behave with luminosity L like

$$\dot{M} \;\sim\; L^{1.7} \,. \tag{1}$$

With the mass–luminosity relation for massive stars, this gives

$$L \;\sim\; M^2 \quad\rightarrow\quad \dot{M} \;\sim\; M^{3.4} \,. \tag{2}$$

From this, we may estimate the typical timescale for mass loss,

$$t_{\dot{M}} \;\sim\; \frac{M}{\dot{M}} \;\sim\; \frac{1}{M^{2.4}} \tag{3}$$

This is to be compared to the MS lifetime t_{MS}, which for massive stars scales like

$$t_{\mathrm{MS}} \;\sim\; M^{-0.6} \,. \tag{4}$$

With increasing mass, the timescale for mass loss decreases much faster than the MS lifetime. One can also estimate the behavior of the amount ΔM of mass lost,

$$\Delta M \;\sim\; M^{2.8} \quad\rightarrow\quad \frac{\Delta M}{M} \;\sim\; M^{1.8} \,. \tag{5}$$

Thus, not only the amount of mass lost grows with the stellar mass, but even the relative amount of mass loss grows fast with increasing stellar masses, which illustrates the importance of this effect.

Over the last 10 years, it was realized that the effects of rotation, both due to rotational mixing and rotationally enhanced mass loss also largely influence the results and Henny has played a leading role in that Lamers & Cassinelli (1999). Thus, including mass loss in the models without properly treating rotation is meaningless and vice–versa. A first clear example is given by the surface enrichments in nitrogen and helium at the surface of OB stars, which cannot be accounted by mass loss only. The N/C enhancements reach a factor 3 to 5 for OB stars in the Milky Way and 30 to 50 for stars in the SMC. Neither in the Galaxy and *a fortiori* in the SMC (since mass loss rates are weaker) can these enrichments be explained in term of mass loss only (Maeder & Meynet 2001). Such large enrichments indicate that the internal structure is strongly modified with respect to standard models.

We can estimate the timescale for mixing t_{mix}. The main mixing process in rotating stars (at least when magnetic fields are not present) is shear mixing (Talon & Zahn 1997). The diffusion timescale t_{diff} behaves like the thermal diffusivity K multiplied by the square of the velocity gradient. For a given velocity gradient, one has in the current notation,

$$t_{\mathrm{diff}} \;\sim\; \frac{1}{K} \quad \text{with} \quad K \;=\; \frac{4\,a\,c\,T^3}{3\,\kappa\,\varrho^2\;C_P} \,. \tag{6}$$

Adopting the scaling of T and ϱ from basic homology relations, we get

$$t_{\rm diff} \ \sim \ \frac{1}{M^{1.8}} \ , \tag{7}$$

which is to be compared to (4) and (3) above. This shows that internal mixing also becomes more important for more massive stars, but not as fast as mass loss. Thus, for very large stellar masses stellar winds may dominate. This behavior is, for example, well confirmed by the comparison of final and initial masses (Fig. 8) or by the chemical yields as a function of the initial masses (Fig. 9).

Great care has to be given to both the expression giving the mass loss rates $\dot{M}$ as a function of luminosity, $T_{\rm eff}$ and metallicity Z; see contributions by Henny and colleagues, who are the masters of this fine art (Vink et al. 2000, 2001, Nugis & Lamers 2000). Great care has also to be given on how rotation is treated. Unfortunately many models treat meridional circulation as a diffusion process, i.e. as "a process making a transport from where there is a lot of something to where there is a little", while circulation is an advection, i.e. a motion not necessarily transporting things according to their gradient. This means that even the sign of the transport by circulation may be wrong, when it is considered as a diffusion.

2.1. Anisotropic Mass Loss

The $\dot{M}$ rates not only determines the actual mass of the star at the various stages of its evolution, but they also determine the amount of angular momentum left in the star. This is also a very important quantity, for example for supernova explosions and for the occurrence of Gamma Ray Bursts (GRB's). In this respect, the anisotropic mass loss and a possible magnetic coupling may be of critical significance. Magnetic coupling is of prime importance in solar type stars with a convective envelope. In massive stars, owing to the modest field generally inferior to 10^2 G, the magnetic coupling at the stellar surface does not seem very important.

The von Zeipel theorem states that the local radiative flux F of a rotating star is proportional to the local effective gravity $g_{\rm eff}$. Thus, there is a much larger flux and a higher $T_{\rm eff}$ at the pole than at the equator (Maeder & Meynet 2000). This latitudinal dependence of $T_{\rm eff}$ leads to asymmetric mass loss and also to enhanced average mass loss rates. On a rotating star, one must consider the flux $F(\vartheta)$ at a given colatitude ϑ as given by von Zeipel's theorem,

$$F(\vartheta) = -\frac{L(P)}{4\pi G M_{\star}} g_{\rm eff} [1 + \zeta(\vartheta)] \ . \tag{8}$$

The term $\zeta(\vartheta)$ is in general negligible. The Eddington factor is a local quantity, $\Gamma_\Omega(\vartheta)$ depending on ϑ and rotation. We define it as the ratio of the local flux $F(\vartheta)$ given by the von Zeipel theorem to the maximum limiting local flux, which is

$$F_{\rm lim}(\vartheta) = -\frac{c}{\kappa(\vartheta)} g_{\rm eff}(\vartheta) \ . \tag{9}$$

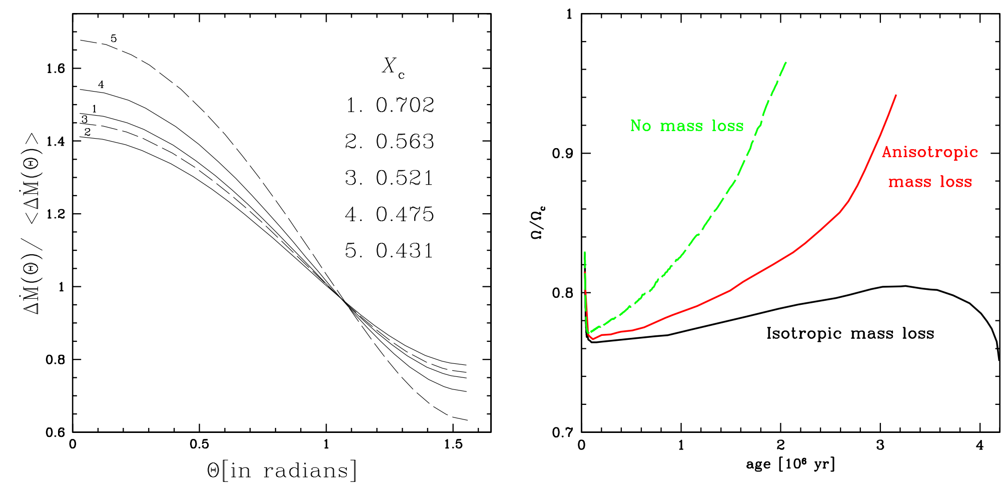

Figure 1. *Left*: Illustration of the anisotropy of the mass flux with colatitude during the MS evolution of a 40 $M_\odot$star with an average velocity of 440 $\mathrm{km\,s^{-1}}$. As the mass fluxes are changing with stellar luminosity and $T_{\rm eff}$ they are normalized in each case to the average value (which is close but not identical to the value at $\vartheta = 1.0$ radian). The horizontal axis is the colatitude in radian, i.e. the pole is to the left, the equator to the right. *Right*: Evolution of the ratio $\Omega/\Omega_{\rm c}$ during the MS phase of a 40 $M_\odot$star model with an initial rotation of 500 $\mathrm{km\,s^{-1}}$. The cases of no mass loss, of isotropic mass loss and of anisotropic mass loss are shown (Maeder 2002).

Thus, one has

$$\Gamma_\Omega(\vartheta) = \frac{F(\vartheta)}{F_{\rm lim}(\vartheta)} = \frac{\kappa(\vartheta)\; L(P)}{4\pi c\, G\, M \left(1 - \frac{\Omega^2}{2\pi G \rho_{\rm m}}\right)} \;, \tag{10}$$

where the opacity $\kappa(\vartheta)$ depends on the colatitude ϑ, since $T_{\rm eff}$ itself depends on ϑ. For electron scattering, the opacity κ is constant over the stellar surface and $\Gamma_\Omega(\vartheta)$ is the same at all latitudes, i.e.

$$\Gamma_\Omega = \frac{\Gamma}{\left(1 - \frac{\Omega^2}{2\pi G \rho_{\rm m}}\right)} \;, \tag{11}$$

where $\Gamma = L/(4\pi\, c\, G\, M)$ is the usual expression. Eq. (11) shows that the maximum luminosity of a rotating star is reduced by rotation. We see that the dependencies of $F(\vartheta)$ and of $F_{\rm lim}(\vartheta)$ with respect to $g_{\rm eff}$ have cancelled each other in the expression of $\Gamma_\Omega(\vartheta)$. Thus, if the limit $\Gamma_\Omega(\vartheta) = 1$ happens to be met at the equator, it is not because $g_{\rm eff}$ is the lowest there, but because the opacity is the highest!

The theory of radiative winds applied to a rotating star leads to an expression of the mass flux as a function of colatitude (Fig. 1 left). For a star hot

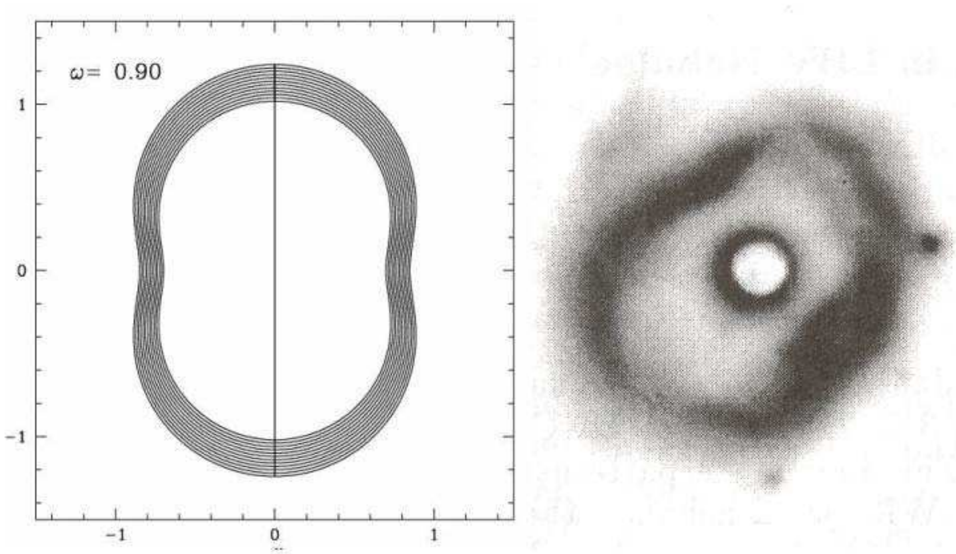

Figure 2. *Left*: simulation of a short shell ejection by a massive star with anisotropic mass loss as in Fig. 1 Left, (Maeder & Desjacques 2000). *Right*: the nebulae around AG Carinae (Nota & Clampin 1997).

enough to have electron scattering opacity from pole to equator, the iso–mass loss curve has a peanut–like shape. This results from the fact that the pole is hotter ("$g_{\rm eff}$–effect"). For a rotating star with a lower $T_{\rm eff}$, a bistability limit, i.e. a steep increase of the opacity (Lamers et al. 1995), may occur somewhere between the pole and the equator. This "opacity–effect" produces an equatorial enhancement of the mass loss. In Fig. 2 left, we show the model of a short shell ejection with mass loss corresponding to the peanut–shape. The corresponding image of AG Carinae (Nota & Clampin 1997) is shown in Fig. 2 right. Thus, rotation remarkably explains the shape of the LBV nebulae, including η Carinae (Maeder & Desjacques 2000).

The anisotropies of mass loss influence the loss of angular momentum. Polar mass loss removes mass, but relatively little angular momentum. This has a great incidence on the evolution of the most massive stars with high rotation. Fig. 1 right illustrates the evolution of the angular velocity at the surface of three different models of a 40 $M_{\odot}$star. With solid body rotation (extreme internal coupling), break–up is quickly reached. For isotropic mass loss and coupling by meridional circulation, the loss of angular momentum prevents the growth of rotation. For anisotropic mass loss with coupling by circulation, the growth of the angular velocity at the stellar surface lies between the two previous cases.

The total mass loss rate $\dot{M}(\Omega)$ of a rotating star compared to that of a non–rotating star at the same location in the HR diagram (Maeder & Meynet 2000) is given by,

$$\frac{\dot{M}(\Omega)}{\dot{M}(0)} \simeq \frac{(1-\Gamma)^{\frac{1}{\alpha}-1}}{\left[1-\frac{4}{9}(\frac{v}{v_{\mathrm{crit},1}})^2-\Gamma\right]^{\frac{1}{\alpha}-1}} \ , \tag{12}$$

where α is a force multiplier (Lamers et al. 1995) and $v_{\mathrm{crit},1} = \left(\frac{2}{3}\frac{GM}{R_{\mathrm{pb}}}\right)^{\frac{1}{2}}$, where R_{pb} is the polar radius at break–up. For a 10 $M_{\odot}$star on the MS (far away from $\Gamma = 1$), the maximum ratio $\dot{M}(\Omega)/\dot{M}(0)$ may reach 1.5. For the most luminous stars which have a value Γ close to 1.0, this ratio may amount to orders of magnitude, when the star reaches break-up at the so–called $\Omega\Gamma$–Limit (see below). For blue and red supergiants, the increase of mass loss could also be large, however supergiants do not rotate fast in general.

Often, the critical velocity in a rotating star is written as $v^2_{\mathrm{crit}} = \frac{GM}{R}(1-\Gamma)$. However, this expression only applies to uniformly bright stars. Indeed, the critical velocity of a rotating star is given by the zero of the equation expressing the total gravity

$$\vec{g}_{\mathrm{tot}} = \vec{g}_{\mathrm{grav}} + \vec{g}_{\mathrm{rot}} + \vec{g}_{\mathrm{rad}} = \vec{g}_{\mathrm{eff}}\left[1-\Gamma_{\Omega}(\vartheta)\right] \ . \tag{13}$$

This equation has two roots (Maeder & Meynet 2000). The first root that is met determines the critical velocity. The first root is as usual $v_{\mathrm{crit},1}$, defined above. The second root $v_{\mathrm{crit},2}$ applies to Eddington factors bigger than 0.639. It is equal to 0.85, 0.69, 0.48, 0.35, 0.22, and 0 times $v_{\mathrm{crit},1}$ for $\Gamma = 0.70$, 0.80, 0.90, 0.95, 0.98 and 1.00 respectively. Thus, the combination of rotation and effects of radiation pressure reduces the critical velocities. This applies to stars at the so–called $\Omega\Gamma$–Limit.

On the whole, we may distinguish three critical cases, where the outer layers escape:

- The usual Γ–Limit, when radiation effects largely dominate over rotation; this is the classical case.
- The Ω–Limit, when rotation effects, rather than radiative effects, are determining break–up. This is relevant for Be-stars, which are far enough from the conditions for Γ to be equal to unity.
- The $\Omega\Gamma$–Limit, when both rotation and radiation are important.

This last case applies to the most massive stars. *Even for a rather small initial rotation velocity of, say,* ≥ 50 *km s*$^{-1}$*, a star with a high* Γ *will reach critical velocity during its MS evolution.* This occurs because the rotation velocity increases during MS evolution, while the critical velocity, which is given by $v_{\mathrm{crit},2}$, decreases. The mass loss rates increase strongly (cf. Eq. 12), when the critical $\Omega\Gamma$–Limit is approached. Such a situation has already been considered (Langer 1997), however for the case of solid body rotation, while here the evolution of the angular momentum is followed with appropriate critical velocity and mass loss expressions as well as a detailed treatment of meridional circulation.

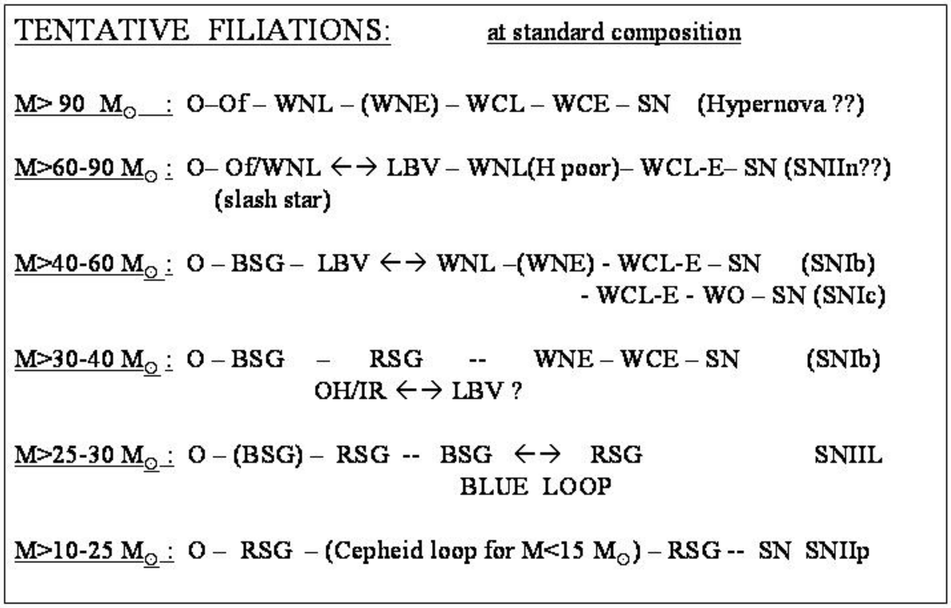

Figure 3. Tentative filiations of massive stars at standard composition. The filiations and mass limits depend on metallicity and rotation. The stages in parentheses indicate relatively short phases. The arrows in two directions indicate possible back and forth evolution.

3. Evolutionary Filiations

Models of massive star evolution with mass loss and rotation have been calculated at solar metallicity, as well as other metallicities (Meynet & Maeder 2003, 2005). The mass loss rates for massive stars are from various sources (Vink et al. 2000, 2001, Nugis & Lamers 2000).

The filiations of the various kinds of massive stars is a relatively complex problem. A tentative representation is given in Fig. 3, some uncertainties still remain. Also, at different metallicities Z, for different mass loss rates and for different rotation velocities, these filiations may be different. An example of such a change of evolutionary filiation due to rotation is illustrated in Fig. 4 left, where one may see the evolution as a function of the rotation velocities of the blue and red supergiant lifetimes. This concerns the metallicity of the SMC. It is quite interesting to see that at zero rotation, most of the He–burning phase is spent as a blue supergiant, while for significant velocities, an increasing fraction of the He–burning phase is spent in the red supergiant phase. Such an effect has enabled us (Maeder & Meynet 2001) to solve the long standing problem (Langer & Maeder 1995) of the blue to red ratio in the SMC and lower Z galaxies. The observations show a large fraction of red supergiants, while the low Z models appropriate for the SMC composition and with zero rotation only predicted blue supergiants.

4. The Evolution of Rotational Velocities

The evolution of the rotation velocities at the stellar surface depends mainly on two facts: the internal coupling and the mass loss rates.

1.– The most extreme case of strong coupling is the classical case of solid body rotation. In this case, when mass loss is small, the star reaches the critical velocity during the MS phase more or less quickly depending on the initial rotation (Langer 1997). The spinning–up of the core, as it gets more concentrated during evolution, is transferred to the surface by the strong coupling. Let us recall that Ω/Ω_c increases when the radius of the star increases, if $\alpha > -3/2$ for a rotation law of the form $\Omega \propto r^{-\alpha}$. Conversely, in case of no coupling (α tends toward -2), i.e. of local conservation of the angular momentum, rotation becomes more and more subcritical. In our models, the situation is intermediate, with a moderate coupling due mainly to meridional circulation, which is more efficient than shear transport, as far as the transport of angular momentum is concerned.

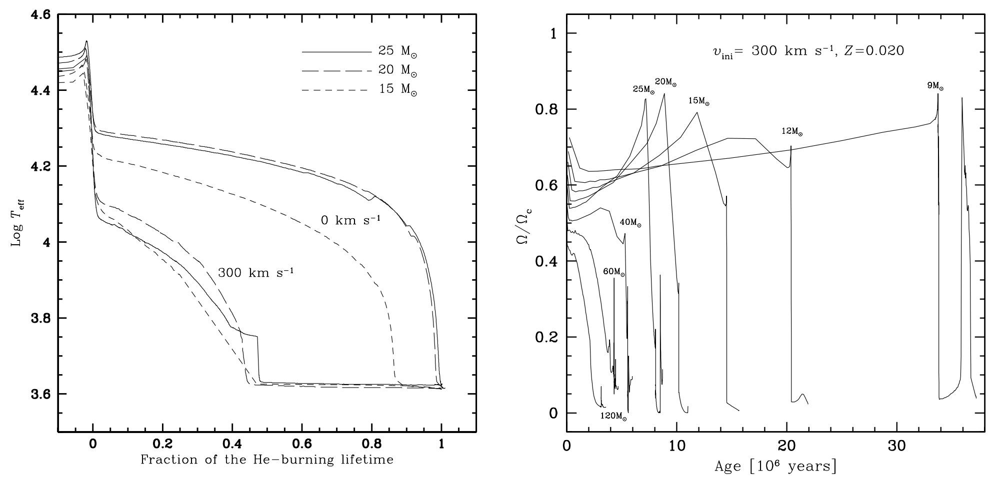

Figure 4. *Left*: Evolution of $T_{\rm eff}$ as a function of the fraction of the lifetime spent in the He–burning phase for various stellar masses with different initial velocities at $Z = 0.004$ appropriate for the SMC (Maeder & Meynet 2001). *Right*: Evolution of the fraction $\Omega/\Omega_{\rm c}$ of the angular velocity to the critical angular velocity at the surface of star models of different initial masses between 120 and 9 $M_\odot$with account of anisotropic mass loss during the MS phase at $Z = 0.02$ (Meynet & Maeder 2003).

2.– For a given degree of coupling, *the mass loss rates play a most critical role in the evolution of the surface rotation*. For models at $Z = 0.02$ and for masses greater than 20 $M_\odot$, the models have velocities which decrease rather rapidly as illustrated by Fig. 4 right. This figure shows the evolution of the fraction $\Omega/\Omega_{\rm c}$ of the angular velocity to the critical angular velocity at the surface of star models of different initial masses between 120 and 9 $M_\odot$with account of anisotropic mass loss during the MS phase. The mass loss rates meet a bi–stability limit at log $T_{\rm eff}$ = 4.40 (Vink et al. 2000, 2001). Below this value there is a sudden increase of the mass loss rates, which makes the rotation velocities to rapidly decrease, to some extent as for the most massive stars. Any comparison between observed and predicted rotation for this domain of mass is really much more a test bearing on the mass loss rates than a test on the internal coupling and evolution of rotation. For initial velocities $v_{\rm ini} \leq 300$ km s^{-1}, the account for the anisotropic wind does not play a major role.

On the contrary, at lower metallicities such as $Z = 0.004$, the rotation velocities would go up for all masses except the largest ones (Maeder & Meynet 2001). In the extreme case of very low Z stars (Meynet & Maeder 2002), even stars with a moderate initial rotation reach break–up during MS evolution.

Below a mass of about 12 $M_\odot$, the mass loss rates are smaller and cease to dominate the evolution of rotation velocities, the internal coupling is then playing the main role in the evolution of the rotational velocities. This provides an interesting possibility of tests on the internal coupling by studying the differences of rotational velocities for stars at different distances of the ZAMS. In particular, such a study could allow us to test the role or absence of role of magnetic coupling in radiative envelopes, which is now a major open question regarding stellar rotation (Spruit 2002).

5. Evolution of the Chemical Abundances

Fig. 5 shows the evolution of the surface abundances in a rotating and a non–rotating model with initial masses of 60 $M_\odot$. The progressive changes of the abundances of CNO elements between the initial cosmic values and the values of the nuclear equilibrium of the CNO cycle are much smoother for the rotating model than for the case without rotation. This is due to the internal mixing which makes flatter internal chemical gradients for rotating models. The rotational mixing also makes the change of abundances to occur much earlier in the peeling–off process leading to WR stars. This is also true for the changes of H and He. Another significant difference for the 60 $M_\odot$model with rotation is the absence of an LBV phase. This statement is however somehow uncertain due to the difficulty to define what is exactly an LBV. At least, one can say that with rotation, the models reach a stage fast with a relatively high He–content, typical of WR stars. Indeed, without rotation, most of the changes of CNO abundances probably occur in the LBV phase, while in the case with rotation, the transition from cosmic to CNO equilibrium abundances occurs smoothly, partly during the MS phase and partly during the phase which immediately follows it. We note that the nuclear equilibrium CNO values are essentially model independent, as already stressed long time ago (Smith & Maeder 1991). This is true whether H is still present or not.

At the end of the WNE phase, the transition to the WC abundances is very sharp in the absence of rotational mixing, because of a strong chemical discontinuity in the classical models, due to the fact that the convective core is usually growing during some part of the He–burning phase. In the rotating model, the transitions are smoother due to chemical mixing, so that there are some stars observed with abundances in the transition regime, with simultaneously some ^{12}C

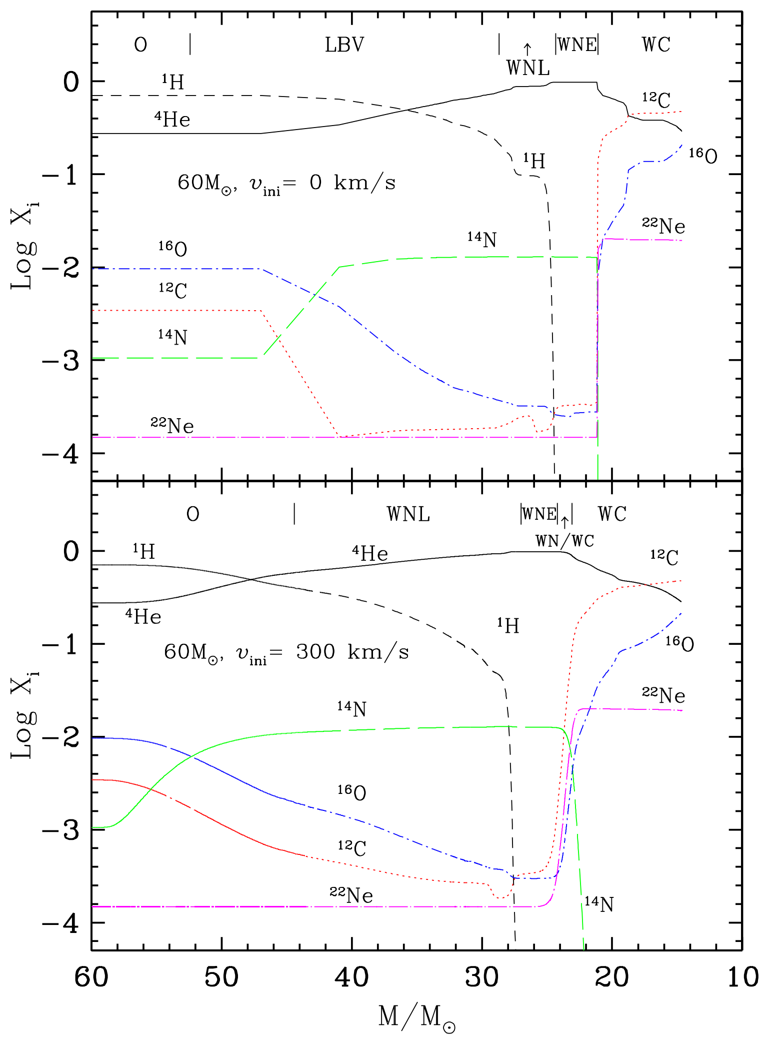

Figure 5. Evolution as a function of the actual mass of the abundances (in mass fraction) at the surface of a non–rotating (upper panel) and a rotating (lower panel) 60 $M_\odot$stellar model of solar composition (Meynet & Maeder 2003).

and some ^{14}N present. These stars likely correspond to the so–called WN/WC stars (Conti & Massey 1989); see end of Sect. 6.

Fig. 6 left shows an interesting diagram for the study of so–called "slash stars" of type Ofpe/WN, of the LBV and of the WN stars. It presents the evolution of the surface H–content as a function of the luminosity. The tracks go downwards in this diagram, firstly there is an initial brightening due to MS evolution, then the luminosity keeps about constant, except for $X_s \leq 0.20$, which happens when the mass loss is very high. Thus for stars above or equal to 25 $M_\odot$this diagram is sensitive to both mass loss and mixing. For masses below

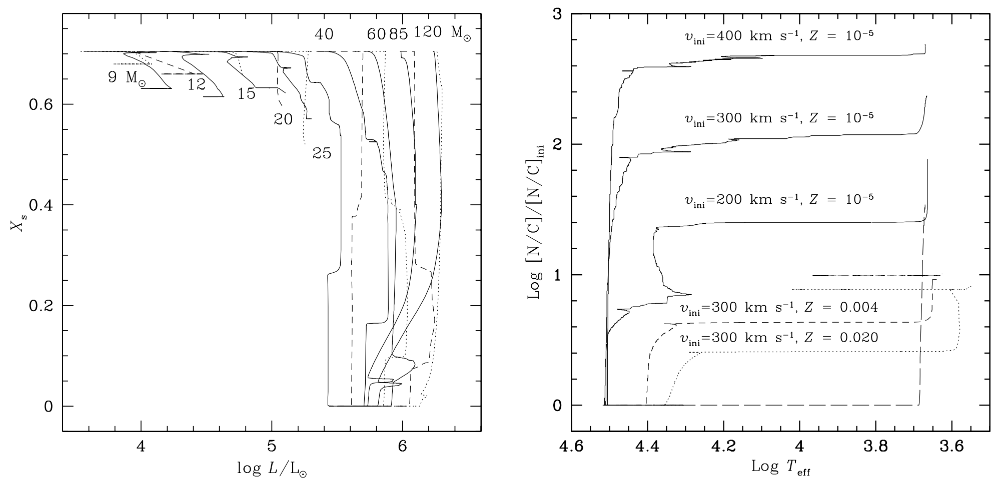

Figure 6. *Left:* Evolutionary tracks in the X_s versus log $L/L_\odot$ plane, where X_s is the hydrogen mass fraction at the surface. The continuous lines are for the rotating models, the dotted or dashed–lines are for the non–rotating models. *Right:* Evolution of the N/C ratio in number for a 9 $M_\odot$star of different Z and $v_{\rm ini}$. Zero rotation gives no enrichment until the red giant stage (Meynet & Maeder 2002).

25 $M_\odot$this diagram indicates up to which stage heavy mixing is proceeding for stars of different luminosities, which is also a useful indication.

The surface enrichments are much larger at lower metallicities. At $Z = 10^{-5}$, the relative increase of the N/C ratios may reach two orders of magnitude with respect to the initial N/C ratio at the considered metallicity (Fig. 6 right). The reason is the steepest internal gradient of Ω (Maeder & Meynet 2001), which favors a strong mixing at low Z. This is illustrated in the case of a star of 9 $M_\odot$. This mixing makes the evolution of lower Z star significantly different from the case of solar metallicity. The mixing may even be larger if the rotation velocities are even higher at lower Z (Chiappini et al. 2006).

6. Evolution and WR Stars

The WR lifetimes for different metallicities Z are plotted as a function of the initial mass in Fig. 7. The metallicity dependence of the mass loss rates is responsible for two features: 1) For given initial mass and velocity, the WR lifetimes are greater at higher metallicities. Typically at Z=0.040 and for M > 60 $M_\odot$, the WR lifetime is of the order of 2 Myr, while at the metallicity of the SMC the WR lifetimes in this mass range are between 0.4–0.8 Myr. 2) The minimum mass for a single star to evolve into the WR phase is smaller at higher metallicity. Rotation has a similar effect as an enhancement of the mass loss rates on the WR lifetimes. Namely, for a given initial mass rotation increases the WR lifetime and also lowers considerably, due to internal mixing, the minimum initial mass of single stars going through a WR phase.

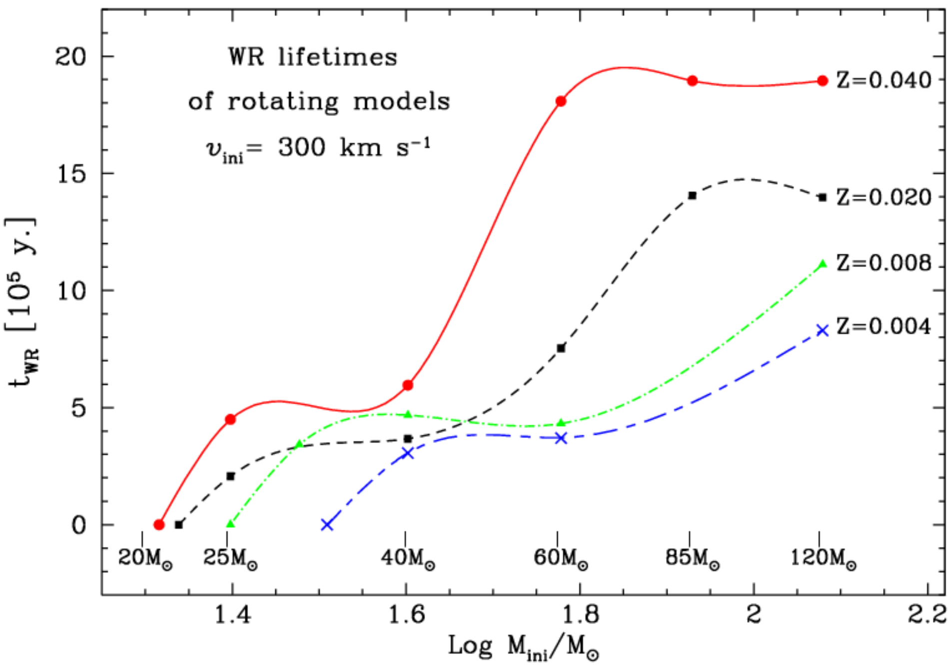

Figure 7. Lifetimes of Wolf–Rayet stars from various initial masses at four different metallicities. All the models begin their evolution with $\upsilon_{\rm ini}$ = 300 km s^{-1} on the ZAMS (Meynet & Maeder 2005).

Concerning the WR sub–phases, rotational mixing during the MS phase increases the duration of the WNL phase, especially at higher metallicities. This occurs because mixing makes a faster increase in the He– and N–contents at the surface and the higher mass loss rates by stellar winds enable the star to enter the WR phase at an earlier stage. The WNE phase is also longer at higher metallicity (this is also the case for non–rotating models). The WC phase keeps more or less the same duration for all the metallicities in the higher mass star range. In the lower mass star range, the WC phase is longer at higher Z as a result of the shift toward a lower minimum initial mass for Wolf–Rayet star formation.

In the rotating stellar models, a new phase of modest, but non–negligible duration, appears: the so–called transition WN/WC phase. This phase is characterized by the simultaneous presence at the surface of both H– and He–burning products. The reason for this is the shallower chemical gradients which build up inside the rotating models. These shallower gradients inside the stars also produce a smoother evolution of the surface abundances as a function of time (see Fig. 5). For a transition WN/WC phase to occur, it is necessary to have –for a sufficiently long period– both an He–burning core and a CNO–enriched envelope. In general, in the highest mass stars, mass loss removes the CNO–enriched envelope too rapidly to allow a long transition WN/WC phase to occur. In the low mass range, the time spent in the WR phase is too short and the

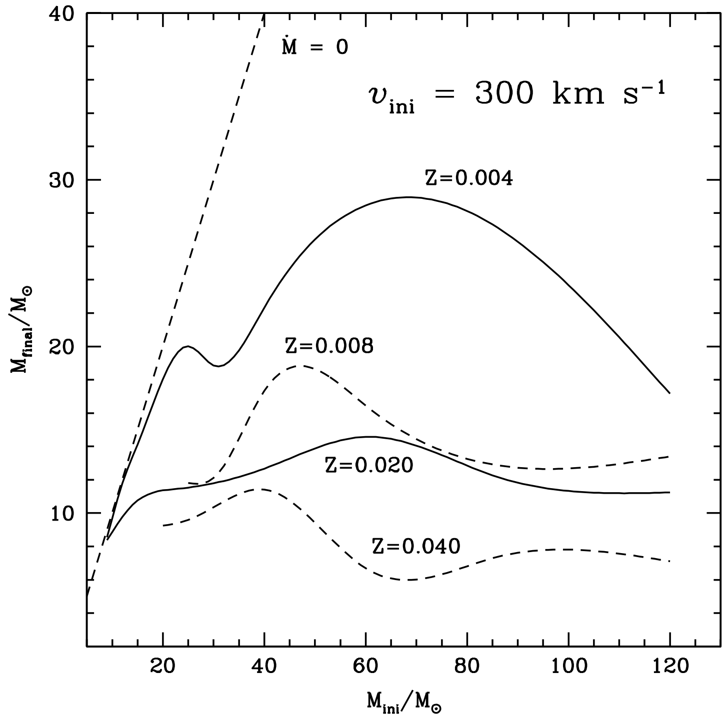

Figure 8. Relations between final and initial mass for rotating stellar models at various metallicities. The line with slope one, labeled $\dot{M} = 0$, corresponds to the case without mass loss (Meynet & Maeder 2005).

H–rich envelope too extended to allow He–burning products to diffuse up to the surface. Consequently, a significant transition WN/WC phase only appears in an intermediate mass range between $\sim$ 30 and 60 $M_\odot$for average rotation velocities. These transition stars also have some ^{22}Ne excess. Since the attribution of spectral types is a complex matter, some of the stars in the transition stage may be given a spectral type WNE or WC. Thus, this may account for WN stars with some ^{22}Ne excess or for WC stars with some ^{14}N present (Willis 1999, Dessart et al. 2000).

7. Mass Loss, Rotation and the Chemical Yields

The importance of mass loss in stellar evolution could not be better illustrated than by the relations between the final masses at the time of supernovae explosion and the initial stellar masses, as shown in Fig. 8 for various metallicities. The models are based on the expression of the mass loss rates as a function of metallicity given by (Kudritzki 2002). For the very low and zero Z, the uncertainties on the final masses are still large. The values of the final masses are critical for determining the types of supernovae and also for nucleosynthesis, because, as is evident, what is escaping in the winds is not further nuclearly processed and this greatly influences the chemical yields.

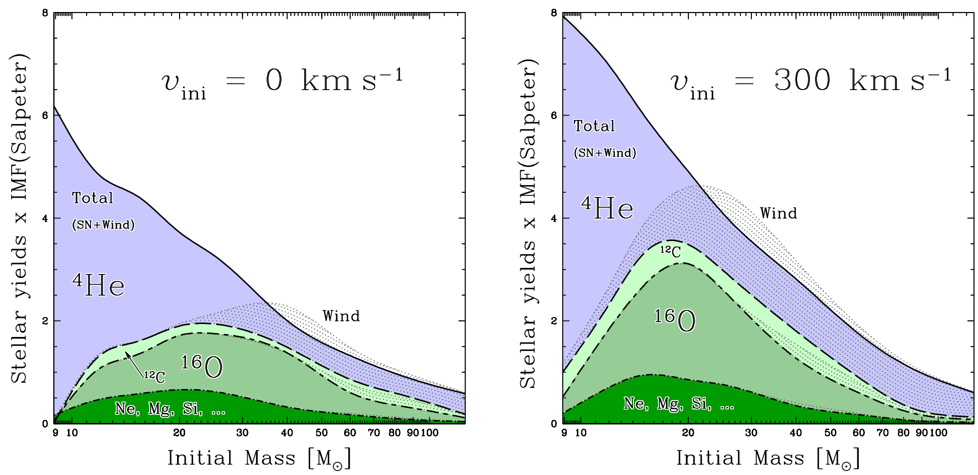

Figure 9. Product of the stellar yields, $mp_{im}^{\rm tot}$ by Salpeter's IMF (multiplied by an arbitrary constant: 1000 x $M^{-2.35}$), as a function of the initial mass for non–rotating (left) and rotating (right) models at solar metallicity. The different shaded areas correspond from top to bottom to $mp_{im}^{\rm tot}$ x 1000 x $M^{-2.35}$ for ^{4}He, ^{12}C, ^{16}O and the rest of the heavy elements. The dotted areas show for ^{4}He, ^{12}C and ^{16}O the wind contribution. Note that for ^{4}He, the total yields is smaller than the wind yields due to negative SN yields (Hirschi et al. 2004).

The model evolution of rotating stars at standard composition has been pursued up to the presupernova stage (Hirschi et al. 2004), since we know that nucleosynthesis is also influenced by rotation. Fig. 9 shows the chemical yields at Z = 0.02 from models without and with rotation, weighted by the initial mass function (IMF). The main conclusion is that below an initial mass of 30 $M_\odot$, the cores are larger and thus the production of α–elements is enhanced. Above 30 $M_\odot$, mass loss is the dominant effect and more He is ejected before being further processed to heavy elements such as oxygen, while the size of the core is only slightly reduced. On the whole, when integrated over the IMF the production of oxygen and of α–elements is globally enhanced, while the effect concerning the He–production in massive stars remains limited.

8. Mass Loss at Very Low Z

Contrarily to current beliefs, strong mass loss may also be present at very low metallicities Z. This results from rotational effects, both by the rotational enhancement of the mass loss as well as due to the fact that the stars reach break–up. Models of massive stars at $Z = 10^{-8}$ and $Z = 0$ have been made (Meynet et al. 2006). These models lose a large fraction of their initial mass, even for the usual parametrization of the mass loss rates.

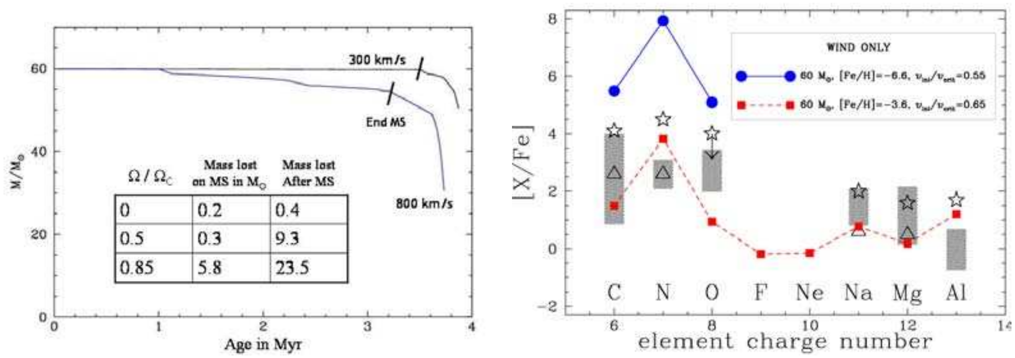

Figure 10. *Left*: Amount of mass lost by stars with an initial mass of 60 $M_{\odot}$at $Z = 10^{-8}$ and with different ratio Ω/Ω_c as a function of age. The small table indicates the values of the mass lost. *Right*: Chemical composition of the wind ejecta of 60 $M_{\odot}$models: solid circles and triangles correspond to models at $Z = 10^{-8}$ ([Fe/H]=-6.1) with and without rotation. The [N/Fe] ratio for the non-rotating model is equal to 0, i.e. no N-enrichment is expected. The hatched areas (leftward lines from top) correspond to the range of values measured at the surface of giant carbon enriched metal poor (CEMP) stars. The various symbols show data from various sources (Meynet et al. 2006).

There are 4 phases where such stars lose mass:

1.– Firstly, during the MS phase very low Z stars easily reach break–up. As the stellar core is shrinking during evolution it spins very fast. Due to the very strong coupling which exists at very low Z, the surface rotation rapidly reaches critical velocities and some mass is lost during the MS phase (cf. Fig. 10, left). An initial rotation of 800 km s^{-1} corresponds in this low radius model to a fraction of about 2/3 of the initial critical velocity.

2.– When the star moves to the red supergiant stage, the strong rotational shear drives internal mixing, which produces surface enrichments in heavy elements. The increase may amount to several orders of magnitude. Thus, an initial $Z = 10^{-8}$ star may reach in the red supergiant stage about the metallicity of the Magellanic Clouds, which will favor heavy mass loss, especially more if the content of the atmosphere in C and O is high.

3.–Massive stars may leave the red supergiant branch due to mass loss and mixing and evolve to the blue. This means that the outer convective zone will contract a lot and it again reaches the critical velocity (Heger & Langer 1998).

4.– As a result of all these effects, the star may lose a lot of mass. In the example of a 60 $M_{\odot}$star with $Z = 10^{-8}$, the total amount of mass lost may reach about half its initial mass (cf. Fig. 10, left). The stars may then enter the WR stage, where mass loss is favored by the high L/M ratio.

A most important point is that these rotational winds contribute to the chemical yields. Their composition is very peculiar, with major enrichments in C, N, O elements. The matter from the winds is further diluted with the supernova ejecta. The contributions of the different masses must be accounted for, even if it is generally assumed that at very low Z massive stars dominate. We note that massive stars initially rotating at half their critical velocity are likely to avoid a Pair–Instability supernova.

The chemical composition of the rotationally enhanced winds of very low Z stars is very peculiar and compares well with observations as shown in Fig. 10 right (Meynet et al. 2006). The winds show large CNO enhancements by factors of 10^3 to 10^7, together with large excesses of ^{13}C and ^{17}O and moderate amounts of Na and Al. The excesses of primary N are particularly striking.

While N–excesses are current in stellar evolution with mixing, the simultaneous relatively large enrichments in C, N and O require a very significant migration of ^{12}C from the He–burning core to the H–shell burning. At very low Z, the process is favored by the great proximity of the H–burning shell to the He–burning core. When these ejecta from the rotationally enhanced winds are diluted with the supernova ejecta from the corresponding CO cores, we find [C/Fe], [N/Fe], [O/Fe] abundance ratios very similar to those observed in the C–rich extremely metal poor stars (CEMP) as illustrated in Fig. 10 right.

Rotating AGB stars and rotating massive stars have about the same effects on the CNO enhancements. Abundances of s-process elements and the ^{12}C/^{13}C ratio could help us to distinguish between contributions from AGB and massive stars. On the whole, one may emphasize the dominant effects of rotational mass loss for the chemical yields of the first star generations, an effect which has strongly influenced the early chemical evolution of galaxies (Chiappini et al. 2006). Amazingly, the strong mass loss by stellar winds in the early stellar generations also seems to be the only way to solve the enigma of the large fraction of He–rich stars on the Main–Sequence of the globular cluster ω Centauri (Maeder & Meynet 2006). These He–rich stars are likely to have been enriched mainly by stellar wind contributions of previous stellar generations.

9. Conclusions

The remarkable point about mass loss is that it intervenes quite generally in stellar evolution. In star formation, the protostars lose a lot of their initial mass before they reach the MS. Mass loss evidently dominates the evolution of massive stars, typically above 30 $M_{\odot}$. It has a complex interaction with rotation, in particular due to asymmetric mass loss and due to rotational mixing. Mass loss seems also very significant at very low metallicities: the stars reach break–up and lose a lot of mass. The signatures of the peculiar winds is present in extremely metal poor halo stars and may have affected the early chemical evolution of galaxies in an important way.

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