Massive Stars as Cosmic Engines Through the Ages

André Maeder[1], Georges Meynet[1], Sylvia Ekström[1], Raphael Hirschi[2] and Cyril Georgy[1]

[1]Geneva Observatory, University of Geneva, CH–1290 Sauverny, Switzerland
email: `andre.maeder@obs.unige.ch, georges.meynet@obs.unige.ch,`
`sylvia.ekstrom@obs.unige.ch, cyril.georgy@obs.unige.ch`
[2]Astrophysics, EPSAM, University of Keele
email: `r.hirschi@epsam.keele.ac.uk`

Abstract. Some useful developments in the model physics are briefly presented, followed by model results on chemical enrichments and WR stars. We discuss the expected rotation velocities of WR stars. We emphasize that the (C+O)/He ratio is a better chemical indicator of evolution for WC stars than the C/He ratios. With or without rotation, at a given luminosity the (C+O)/He ratios should be higher in regions of lower metallicity Z. Also, for a given (C+O)/He ratio the WC stars in lower Z regions have higher luminosities. The WO stars, which are likely the progenitors of supernovae SNIc and of some GRBs, should preferentially be found in regions of low Z and be the descendants of very high initial masses. Finally, we emphasize the physical reasons why massive rotating low Z stars may also experience heavy mass loss.

Keywords. stars: early-type – stars: Wolf-Rayet – stars: rotation – stars: mass loss

1. Introduction

It may be worth to quote a few of the important findings which have led to the development of our field. Fifty years ago, Peter Conti *et al.* (1967) found that metal deficient stars have higher O/Fe ratios than the solar ratio. This was the first finding concerning differences of abundance ratios as a function of metallicity, due to a different nucleosynthesis in early stages of galactic evolution. A year after, Lindsey Smith (1968) remarkably found that the various subtypes of WR stars are differently distributed in the Galaxy and that some subtypes are missing in the LMC. The outer galactic regions and the LMC showing the same kind of WC stars (early WC). This was the first evidences of different distributions of massive objects in galaxies. A great discovery from Copernicus and from IUE is the mass loss from O–type stars by Morton (1976, see also Henny Lamers & Donald Morton 1976). The interpretation of WR stars as post-MS stars resulting from mass loss in OB stars was proposed by Peter Conti (1976).

Of course, there are many other big steps which have contributed to our knowledge about massive stars. It would be misleading to believe that these findings were smoothly accepted as such. For at least a decade, there were people claiming that mass loss is an artifact or disputing the status of WR stars, even considering them as pre–MS stars. These controversies, on the whole, contributed to further checks and investigations which eventually resulted in an increased strength of the initial discoveries.

2. Improved Model Physics in Massive Star Evolution

The physics and evolution of massive stars is dominated by mass loss and by rotational mixing. At the origin of both effects, we find the large ratio T/ρ of temperature to density
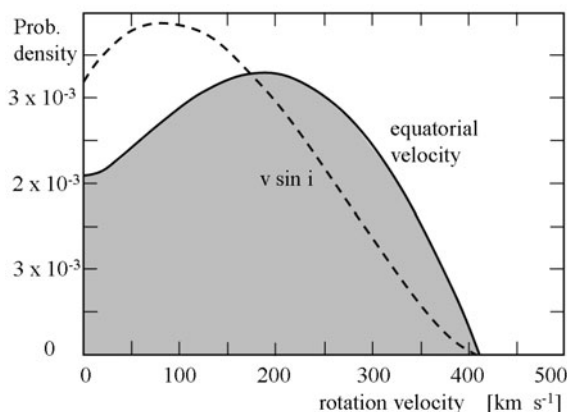
Figure 1. Probability density by km s^{-1} of rotation velocities for 496 stars with types O9.5 to B8. Adapted from Huang and Gies (2006a)

in massive stars. This enhances the ratio of radiation to gas pressure, which goes like

$$\frac{P_{\mathrm{rad}}}{P_{\mathrm{gas}}} \sim \frac{T^3}{\rho} \; . \tag{2.1}$$

The high T/ρ favors mass loss by stellar winds. A large fraction of OB stars have high rotational velocities (Fig. 1). A high T/ρ also enhances rotational mixing either by shear diffusion or meridional circulation, since the coefficient of mixing for a vertical shear dv/dz behaves as

$$D_{\mathrm{shear}} = 2\,\mathcal{R}i_{\mathrm{crit}}\, K\, \frac{(dv/dz)^2}{N_{\mathrm{ad}}^2} \; . \tag{2.2}$$

$\mathcal{R}i_{\mathrm{crit}}$ is the critical Reynolds number and N_{ad} is the adiabatic Brunt–Väisälä frequency. The diffusion coefficient scales as the thermal diffusivity $K = 4acT^3/(3C_{\mathrm{P}}\,\kappa\,\rho^2)$. Similarly, the velocity of meridional circulation scales as the ratio L/M of the luminosity to mass. Thus, the high T/ϱ favors both mixing and mass loss, the account of both effects brings major revisions of the model results.

For meridional circulation, self–consistent solutions were proposed by Zahn (1992) and Maeder and Zahn (1998). The transport of chemical elements obeys a classical diffusion equation. More critical is the equation for the transport of the angular momentum

$$\frac{\partial}{\partial t}(\varrho\, r^2 \sin^2 \vartheta\, \Omega)_r + \frac{1}{r^2} \frac{\partial}{\partial r}(\varrho\, r^4 \sin^2 \vartheta\, U_r \Omega) + \frac{1}{r \sin \vartheta} \frac{\partial}{\partial \vartheta}(\varrho\, r^2 \sin^3 \vartheta\, U_\vartheta \Omega)$$

$$= \frac{\sin^2 \vartheta}{r^2} \frac{\partial}{\partial r}\left(\varrho\, D_{\mathrm{shear}} r^4 \frac{\partial \Omega}{\partial r}\right) + \frac{1}{\sin \vartheta} \frac{\partial}{\partial \vartheta}\left(\varrho\, D_{\mathrm{h}}\, \sin^3 \vartheta \frac{\partial \Omega}{\partial \vartheta}\right) \; . \tag{2.3}$$

It contains both advection terms depending on U_r and U_ϑ the radial and horizontal components of the velocity of meridional circulation and diffusion terms. D_{h} is the diffusion coefficient by the horizontal turbulence. The self–consistent solutions allow us to follow the evolution of the angular velocity $\Omega(r)$ at each level. Many authors ignore the advection terms or represent them by diffusion terms. This is incorrect, since the circulation currents may turn in different ways (Fig. 2 left).

A big question is whether there is a dynamo working in radiative zones, because a magnetic field would have great consequences on the evolution of rotation by exerting
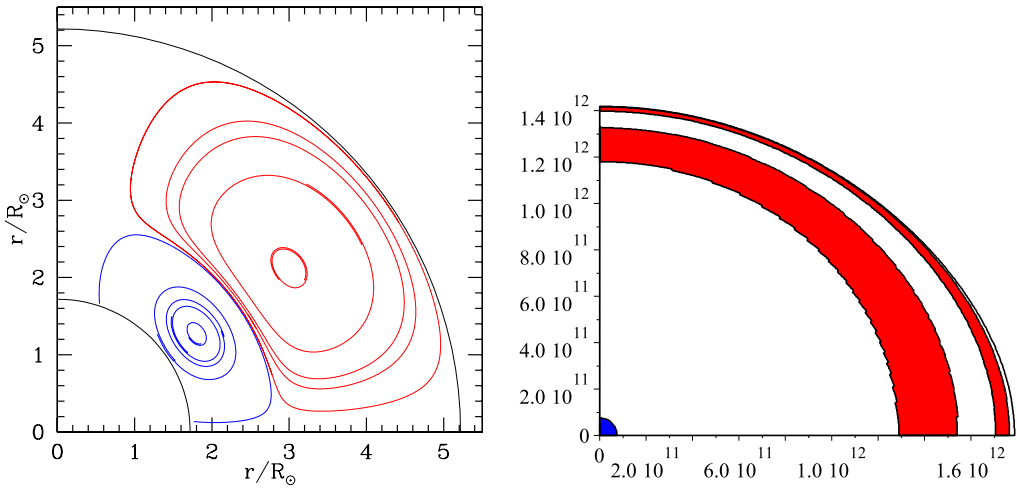
Figure 2. Left: circulation currents in a 20 M$_\odot$ star in the middle of the H–burning phase. The initial rotation velocity is 300 km s^{-1}. The inner loop is raising along the polar axis, while the outer loop, the Gratton–Öpik circulation cell, is going up in the equatorial plane. Right: 2–D representation of the convective zones (dark areas) as a function of radius in a model of 20 M$_\odot$ with $X = 0.70$ and $Z = 0.020$ at the end of MS evolution with ($\Omega/\Omega_{\mathrm{crit}} = 0.94$).

an efficient torque able to reduce the differential rotation or even to impose uniform rotation. A dynamo can operate in the radiative zone of a differentially rotating star thanks to a magnetic instability as shown by Spruit (2002). Let us consider a star with a shellular rotation law $\Omega(r)$ with an initially weak poloidal magnetic field B_r, so that the magnetic forces are negligible (strong initial field leads to solid body rotation). The radial component is wound up by differential rotation. After a few differential turns, an azimuthal field of component B_φ is present, its strength grows linearly in time and the component B_φ dominates over B_r. At some stage, the field B_φ becomes unstable, due to Tayler's instability which is the first instability encountered. The instabilities mainly have horizontal components, but there is also a small vertical component l_r, limited by the action of buoyancy forces. This small radial component of the field is further wound up by differential rotation, which then amplifies the toroidal component of the field up to a stage where dissipation effects would limit its amplitude. In this way, a strong toroidal field develops together with a limited radial field. The horizontal component enforces shellular rotation, while the vertical field component favors solid body rotation. Numerical models by Maeder and Meynet (2005) show that the field is most effective for transporting angular momentum. The displacement due to the magnetic instability also contribute to enhance the transport of the chemical elements.

In addition to the effects of metallicity on the mass loss rates (see contributions by Vink and Crowther, this volume), the interactions of rotation and stellar winds have many consequences. – Rotation introduces large anisotropies in the stellar winds, the polar regions being hotter than the equatorial ones. – The global mass loss rates are increased by rotation. – The anisotropies of the stellar winds allow a star with strong polar winds to lose lots of mass without losing too much angular momentum. At the opposite, equatorial mass loss removes a lot of angular momentum.

Let us consider a rotating star with angular velocity Ω and a non–rotating star of the same mass M at the same location in the HR diagram. The ratio of their mass loss rates can be written, see Maeder (1999),

Figure 3. The filiations between Pop. I massive stars for different mass domains.

$$\frac{\dot{M}(\Omega)}{\dot{M}(0)} \approx \frac{(1-\Gamma)^{\frac{1}{\alpha}-1}}{\left[1 - \frac{4}{9}\left(\frac{v}{v_{\mathrm{crit},1}}\right)^2 - \Gamma\right]^{\frac{1}{\alpha}-1}} . \tag{2.4}$$

The ratio $v/v_{\mathrm{crit},1}$ is the ratio of the rotational velocity v to the critical velocity. If $\Omega = 0$, $v/v_{\mathrm{crit},1}$ is equal to 1. For a star with a small Eddington factor Γ, we can neglect Γ with respect to unity. This equation shows that the effects of rotation on the $\dot{M}$ rates remain moderate in general. However, for stars close to the Eddington limit, rotation may drastically increase the mass loss rates, in particularly for low values of the force multiplier α, i.e. for log $T_{\mathrm{eff}} \leqslant 4.30$. In cases where $\Gamma > 0.639$, a moderate rotation may make the denominator of (2.4) to vanish, indicating large mass loss and instability.

Massive O stars have a small external convective envelope due to their high luminosity. Rotation amplifies these external convective regions (Fig. 2 right). This occurs despite the inhibiting effect of the Solberg–Hoiland criterion, because another more important effect is present in envelopes: the rotational increase of the radiative gradient ∇_{rad} as shown by Maeder *et al.* (2008). These convective zones are likely to play a large role in the origin of the clumping of stellar winds. The matter accelerated in the wind continuously crosses the convective zones in a dynamical process. Convection in the outer layers of O–type stars generates acoustic waves with periods of several hours to a few days. These waves propagate and are amplified in the winds, which have a lower density.

Most remarkably several of these developments lead to the result that the first stars at very low Z have a very different behavior from the present day massive star evolution.

3. Evolution with Mass Loss and Rotation

3.1. *Filiations*

Fig. 3 indicates the possible filiations of massive stars of Pop. I, which can be established from the continuity in the evolution of the chemical abundances, as well as from their properties in star clusters. Globally, one has three main cases.

– For $M > (60-40)M_{\odot}$: the high mass loss rates remove enough mass so that stars lose their envelopes on the MS or in the blue supergiant stage as LBV. The stars never become red supergiants.

– For about 40 to 30 $M_\odot$: the stars only loose a fraction of their envelopes on the MS. They further evolve to the red supergiant stage, where mass loss is sufficient to remove their envelope, they become bare cores and are observed as WR stars.

– Below about 25 to 30 $M_\odot$: the stars still experience mass loss, however it is not sufficient to alter the global evolution. The mass loss and rotation may nevertheless still modify the lifetimes and the chemical compositions.

The mass limits are uncertain and depend on metallicity Z. At different Z, some sequences may be absent. The last indicated stage before supernovae (SN) are usually reached near the end of central He burning. After this stage, the stellar envelopes do not further evolve and their properties determine the nature of the SN progenitors.

Table 1. The largest [N/H] values observed for different types of stars in the Galaxy, LMC and SMC. The average is equal to about the half of the indicated values. See text.

Types of stars	[N/H] in Galaxy	[N/H] in LMC	[N/H] in SMC
O stars	0.8 - 1.0	–	1.5 - 1.7
B–dwarfs $M < 20$ $M_\odot$	0.5	0.7 - 0.9	1.1
B giants, supg. $M < 20$ $M_\odot$	–	1.1 - 1.2	1.5
B giants, supg. $M > 20$ $M_\odot$	0.5 - 0.7	1.3	1.9

3.2. *Chemical Abundances in OB Stars and Supergiants*

The chemical abundances offer tests of stellar physics and evolution. Mass loss, mixing and mass exchange in binaries affect surface compositions. The removal of the outer layers by stellar winds reveal the inner layers with a composition modified by the nuclear reactions in a beautiful illustration of the effects of the CNO cycles and He–burning reactions. Simultaneously, the internal mixing modifies the surface abundances. Without mixing, there would be no nitrogen enrichment during the MS phase for stars with $M < 60$ $M_\odot$. It is only above this value that mass loss can make the products of the CNO cycle to appear at the stellar surface.

The amplitudes of the enrichments of N/H or N/C at the end of the MS phase in massive stars is a reference point telling us the importance of mixing. The main observations in the Galaxy ($Z \approx 0.02$), in the LMC ($Z \approx 0.008$) and in the SMC ($Z \approx 0.004$) at different Z are summarized in Table 1, based on Herrero (2003), Heap *et al.* (2006), Hunter *et al.* (2007), Trundle *et al.* (2007). We notice several facts:

• The N enrichments increase with mass and evolution.
• The N enrichments are larger at lower Z.
• Close to the ZAMS there are both stars with and without N enrichments.
• Away from the ZAMS, but still in the Main Sequence, the N enrichments are larger and they are even larger in the supergiant stages. In B stars, the He excesses are larger as evolution proceeds on the MS and the excesses are greater among the faster rotators as shown by Huang & Gies (2006a, 2006b).

The best credit should be given to the sets of data, where the authors carefully distinguish the mass domains and do not mix in a single plot stars of very different masses. Also, if $\log g$ is taken as an indicator of evolution, the rotational effect on the gravity should be accounted for. Binaries where effects of tidal interactions and mass loss enhancements are possible should be separated from single stars. Finally, error bars should be indicated. Unfortunately, the non–respect of such wise prescriptions is often giving some confusing results.
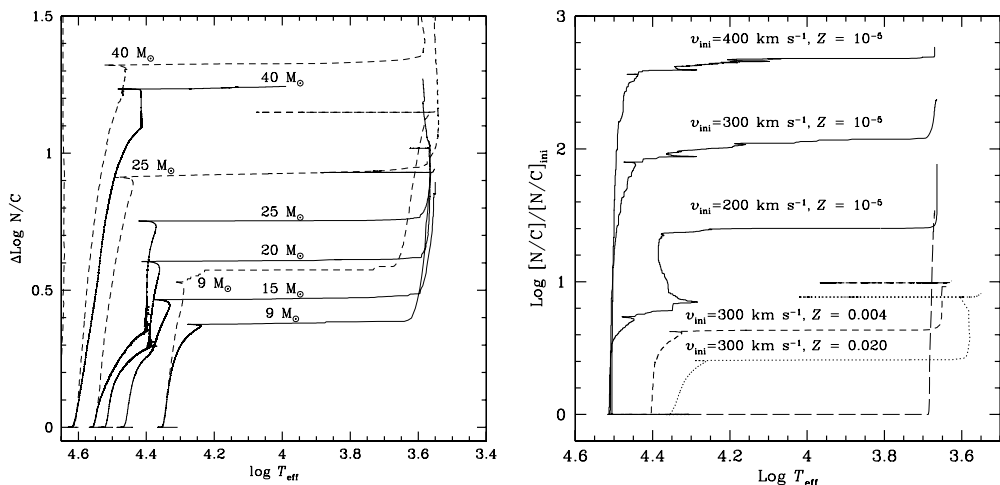
Figure 4. Left: evolution tracks in the plot $\Delta \log(N/C)$ (change with respect to the initial N/C ratio) vs. $\log T_{\rm eff}$ for various initial masses with $Z = 0.02$ with initial velocities 300 km s^{-1} (continuous lines). The dashed lines show the tracks with different model assumptions (Meynet & Maeder 2000). Right: excesses N/C in log scale for a 9 M$_\odot$ star at different metallicities and rotation velocities. The long–dashed line, at the bottom, corresponds to a non–rotating 9 M$_\odot$ stellar model at $Z = 10^{-5}$. From Meynet & Maeder (2002, 2003).

Fig. 4 (left) shows the predicted changes of the $\log(N/C)$ ratios with respect to the initial ratio. Without rotational mixing (dotted lines), there would be no enrichment until the red supergiant stage. Rotation rapidly increases the N/C ratios on the Main Sequence, with a level depending on the velocities. This results from the steep Ω gradients which produce shear diffusion. The predicted N enrichments are in general agreement with the observed effects. The models consistently predict larger N enrichments with increasing stellar masses and more advanced evolutionary stages. If the stars experience blue loops, they have on the blue side of the HR diagram high N/C ratios typical of red supergiants. Thus, B supergiants at the same location in the HR diagram and with the same rotation may have very different enrichments. The $v \sin i$ converge toward low values during the red phase whatever their initial velocities, thus in the yellow and red phases stars of almost identical $v \sin i$ may exhibit different N/C enrichments.

Fig. 4 (right) shows the N/C ratios in models of rotating stars with 9 M$_\odot$ for $Z = 0.02$, 0.004 and 10^{-5}. At $Z = 10^{-5}$ for the 9 M$_\odot$ model and other masses, there is a large N/C increase by one to two orders of magnitude as shown by Meynet & Maeder (2002). These very large enhancements originate from the very steep Ω gradients in rotating stars at low Z, which drive a strong turbulent shear diffusion. Consistently with observations in Table 1, the lower Z models show larger N enhancements. However, the observations in the SMC show larger N/C ratios than the $Z = 0.004$ model of Fig. 4 right and are in better agreement with relatively lower Z models.

4. Rotation and Chemistry of WR Stars

4.1. *Rotation of WR Stars*

Little is known on the rotation of WR stars. Some information has been recently obtained from the co–rotating regions generating periodic variations in spectral lines (see Chené & St-Louis, this volume). The velocities are typically lower than about 50 km s^{-1} in very
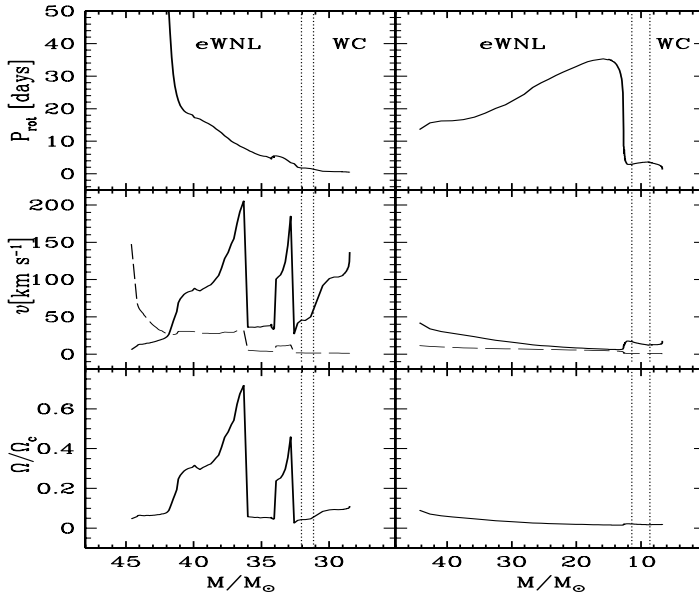
Figure 5. Evolution as a function of the actual mass of the rotation period, of the surface equatorial velocity and of the ratio of the angular velocity to the critical value during the WR stage of rotating stars. The long–dashed lines in the panels for the velocities show the evolution of the radius in solar units. Left: the WR phase of a star with an initial mass of 60 $M_\odot$ with $v_{\rm ini} = 300$ km s^{-1} and $Z = 0.004$. Right: for an initial mass of 60 $M_\odot$ with $v_{\rm ini} = 300$ km s^{-1} and $Z = 0.040$. From Meynet & Maeder (2005).

good agreement with the model predictions. Fig. 5 shows the evolution during the WR stages of the rotation periods $P = (2\pi/\Omega)$, of the rotation velocities v at the equator and of the fractions $\Omega/\Omega_{\rm c}$ of the angular velocity to the critical angular velocity at the surface of star models with an initial mass of 60 $M_\odot$ and $v_{\rm ini} = 300$ km s^{-1} at $Z = 0.004$ and 0.040. The evolution in the WR stages is fast and the transfer of angular momentum by meridional circulation is small, thus at this stage the evolution of rotation is dominated by the local conservation of angular momentum unless there is a magnetic field. The variations of v and $\Omega/\Omega_{\rm c}$ may nevertheless be fast due to the rapid changes of radius in particular when the star loses its last H layers which makes an opacity decrease. The changes of periods are smoother because v and R both decrease at the same pace.

At solar or higher Z, the expected velocities v are small with $v < 50$ km s^{-1}. The reason is that a large part of the WNL phase occurs during the core H–burning phase, where the high mass loss has time to pump the whole internal angular momentum, so that when the star contracts to the WC stage there is almost no rotation left.

At lower Z, the velocities of WR stars are predicted to be higher, e,g. between 30 and 200 km s^{-1} at $Z = 0.004$. The variations of v and $\Omega/\Omega_{\rm c}$ are also greater and more rapid when the radius is changing and the break–up limit might be encountered. The reason is that, at low Z, the WR stage is not entered during the H–burning phase. Despite mass loss, the inner rotation is not killed due to the lack of time.

4.2. *WR Star Chemistry*

Late WN stars (WNL) generally have H present, with an average value at the surface $X_{\rm s} \approx 0.15$, while early WN stars (WNE) have no H left (see Crowther 2007). In the Galaxy, some WNL stars with weak emission lines have $X_{\rm s} \approx 0.50$. Other abundance
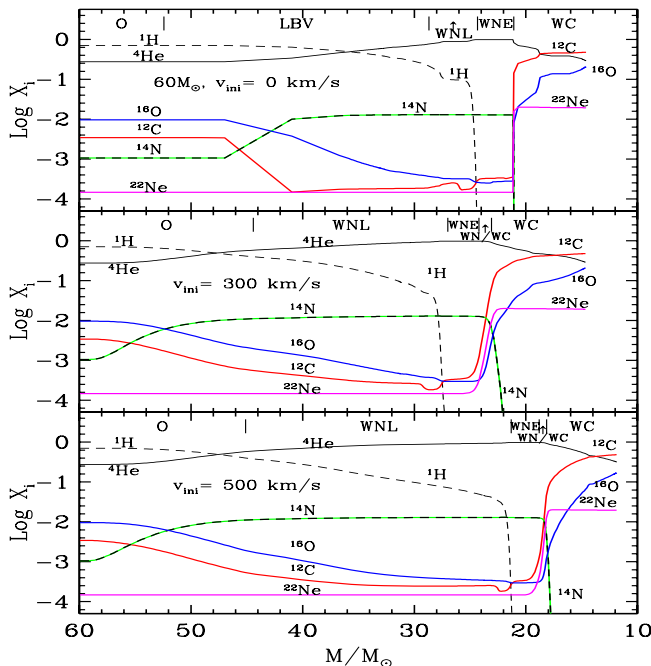
Figure 6. Evolution of the surface abundance for 60 M$_\odot$ models at $Z = 0.02$ for 3 values of the initial velocities. From Meynet & Maeder (2003).

ratios in mass fraction are typically N/He= $(0.035-1.4)\times10^{-2}$, C/He= $(0.21-8)\times10^{-4}$ and C/N= $(0.6-6)\times10^{-2}$. These values are very different from the cosmic values in agreement with model predictions (Fig. 6). The WN abundances are the values of the CNO cycle at equilibrium, they are independent of rotation and are a test of the nuclear cross–sections. At the transition from WN to WC, the rotating models permit the simultaneous presence of ^{14}N, ^{12}C and ^{22}Ne enrichments for a short period of time. This corresponds to the transition WN/C stars, which show mass fractions of N $\sim 1\%$ and C $\sim 5\%$. They represent ~ 4–5 % of the WR stars. Without rotational mixing, there would be no WN/C stars, because of the strong chemical discontinuity at the edge of the convective core in the He–burning phase (Fig. 6). A smooth chemical transition is needed to produce them in the process of peeling–off as shown by Langer (1991).

4.3. *A Fundamental Diagram for WC Stars*

WC stars have mass fractions of C between about 10 and 60% and of about 5–10 % for O, the rest being helium, e.g. Crowther (2007). The variations are smoother in rotating models (Fig. 6). In the WC stage, rotation broadens the range of possible C/He and O/He ratios, permitting the products of He burning to appear at the surface at an earlier stage of nuclear processing with much lower C/He and O/He ratios as suggested by observations.

The destruction of ^{14}N in the He–burning phase leads to the production of ^{22}Ne, which appears at the stellar surface in the WC stage. The models predict Ne enhancements by a factor 20-30. However, the abundance of the CNO elements have been reduced by a factor of ~ 2 and the Ne abundance has been revised upward by Asplund *et al.* (2004). Thus, a new estimate has to be made. ^{22}Ne is the daughter of ^{14}N, which is itself the daughter of CNO elements. The sum of CNO elements is X(CNO)=0.00868, which essentially
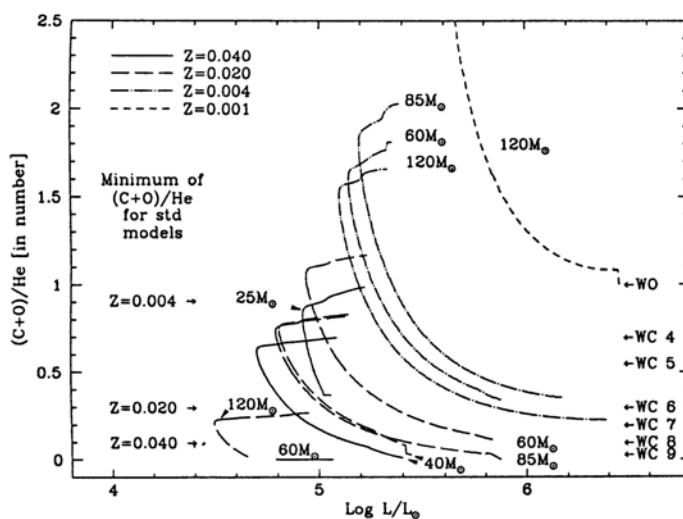
Figure 7. The (C+O)/He ratios in WC stars as a function of L for different Z and initial masses, cf. Maeder & Meynet (1994) and Meynet & Maeder (2005).

becomes ^{14}N. Since two α particles are added to ^{14}N to form ^{22}Ne, the abundance of ^{22}Ne in WC stars should be

$$X(^{22}\mathrm{Ne}) = \frac{22}{14} X(^{14}\mathrm{N}) \quad \text{num.} \quad X(^{22}\mathrm{Ne}) = 1.57 \times 0.00868 = 0.0136\,. \quad (4.1)$$

We get a sum of Ne isotopes of about $X(\mathrm{Ne}) = 0.0156$ compared to $X(\mathrm{Ne})_\odot = 0.0020$. This gives a relative Ne enhancement by a factor of 8, instead of 20 to 30 with the old abundances. The factor of 8 is in excellent agreement with the observations by Ignace *et al.* (2007), who find excesses of 9.

Fig. 7 is a fundamental diagram for the chemical abundances of WC stars. There are versions of this figure with only mass loss and also including rotation by Meynet & Maeder (2005). It shows the (C+O)/He ratios as a function of the luminosity for WC stars of different initial masses and metallicities. At low Z, since mass loss is low, only the extremely massive stars enter the WC stage, thus their luminosities are high, as well as their (C+O)/He ratios. The reason for the high (C+O)/He ratios is that the rare stars which enter the WC stage enter it very late in the process of central He burning or even they do it after He exhaustion.

At higher Z, such as $Z = 0.02$ or $Z = 0.04$, due to the higher mass loss rates less massive stars may become WR stars, thus they have lower luminosities (Fig. 7). As the mass loss rates are higher, the products of He burning appear at an earlier stage of nuclear processing, i.e. with much lower (C+O)/He ratios. These properties seem unavoidable and they are also present in models with rotation (rotation does not alter the relations illustrated by Fig. 7). The coupling between L, Z and the (C+O)/He ratios produces the following consequences, see Smith & Maeder (1991).

• At a given luminosity, the (C+O)/He ratios are higher in regions of lower Z.
• For a given (C+O)/He ratio, the WC stars in lower Z regions have much higher luminosities.
• WO stars, which correspond to an advanced stage of evolution, should according to these predictions preferentially be found in regions of low Z and from very high initial

masses. This is a particularly important aspect since WO stars (with little or no He left) are likely the progenitors of supernovae SNIc, a small fraction of which are accompanied by GRBs.

These model predictions are awaiting observational confirmation. Some of the above trends have been discussed by Smith & Maeder (1991). However, they rest on the early results by Smith & Hummer (1988), who suggested an increase of C/He from WCL to WCE stars. Further studies have put doubts on this relation as shown by Crowther (2007). However, nothing is settled in view of the scarcity of the data on the O abundances. We emphasize it is essential not to just consider the C/He ratios, because during the He burning, C is first going up and then going down. Thus, by just considering the C data one may get misleading results. The (C+O)/He ratios vary in a monotonic way and should be preferred as a test of the abundances of WC stars.

5. Toward the First Stars

It is usually considered that mass loss should be small at very low Z, such as $Z < 10^{-3}$. This is not necessarily true as shown by Meynet & Maeder (2002) and Meynet *et al.* (2006). There are three different effects intervening.

• During the MS phase, the internal coupling of the angular momentum resulting from Eq. (2.3) is sufficient to transmit some of the fast rotation of the contracting core to the stellar surface. Thus, for a large range of initial masses and Ω values the low–Z stars reach the critical velocity during their MS phase (Fig. 8). This produces some moderate mass loss during the MS phase.

• The second effect is due to the self–enrichment of the stellar surface in CNO elements due to internal mixing. There is a remarkable interplay between rotation, mass loss and chemical enrichments in low–Z stars. Low Z implies a weak Gratton–Öpik circulation, which favors high internal Ω–gradients and in turn strong mixing of the chemical elements. The surface enrichments are very important, mainly due to the stellar radii being small (the diffusion timescales vary like R^2). Then, the high surface enrichments in heavy elements, particularly CNO elements, permits radiative winds and mass loss in the He–burning phase of massive and AGB stars.
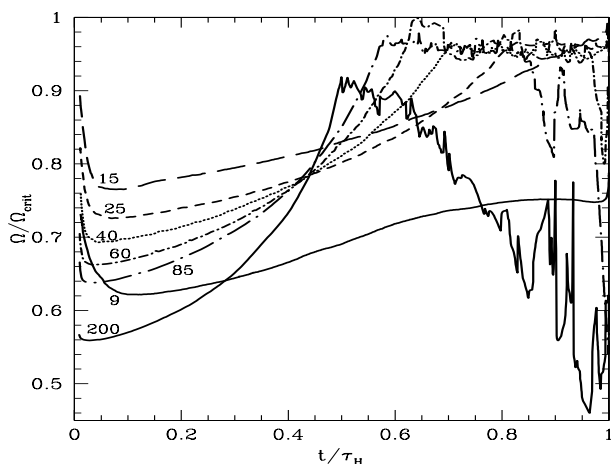

Figure 8. Examples of the evolution of the ratio of the angular velocity Ω to the critical values as a function of the fraction of the MS lifetime for different initial masses at $Z = 0$. From Ekström (2008).
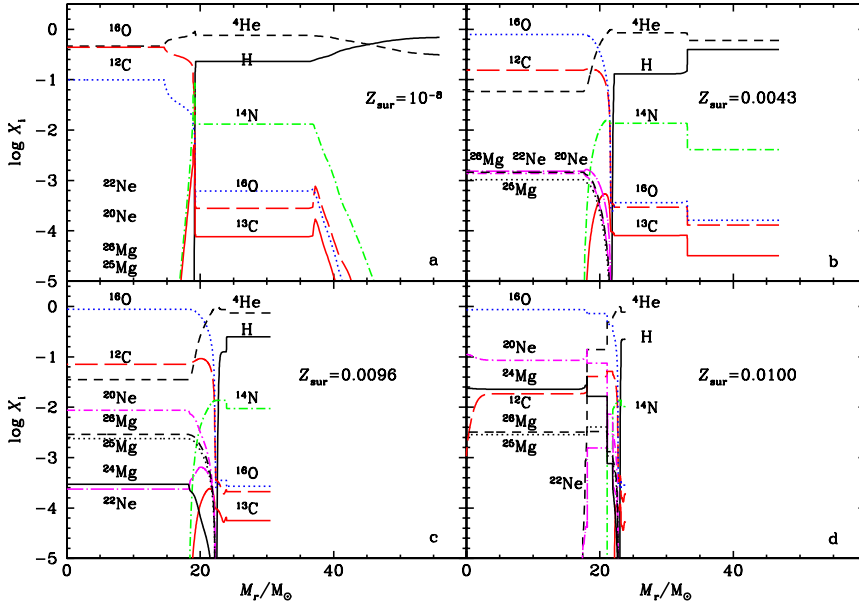
Figure 9. Variations of the abundances (in mass fraction) as a function of the Lagrangian mass within a 60 $M_\odot$ star with $v_{\text{ini}}= 800$ km s^{-1} and $Z = 10^{-8}$. The four panels show the chemical composition at four different stages at the end of the core He-burning phase: in panel **a)** the model has a mass fraction of helium at the centre, $Y_c = 0.11$ and an actual mass $M = 54.8$ M$_\odot$ - **b)** $Y_c = 0.06$, $M = 48.3$ M$_\odot$ - **c)** $Y_c = 0.04$, $M = 31.5$ M$_\odot$ - **d)** End of the core C-burning phase, $M = 23.8$ M$_\odot$. The actual surface metallicity Z_{surf} is indicated in each panel. From Meynet *et al.* (2006).

• The stars with $M < 40$ M$_\odot$, depending on rotation, may make blue trips in the HR diagram. If so, the contraction of the convective envelope brings the surface velocity to critical value and mass loss is enhanced according to Eq. (2.4).

Fig. 9 illustrates the very strong enrichments in CNO during the He–burning phase of 60 M$_\odot$ stars with an initial $Z = 10^{-8}$ and an initial rotation velocity of 800 km s^{-1}. From an initial $Z = 10^{-8}$, the surface metallicity is brought to $Z = 0.01$. This permits the stellar winds of red supergiants and AGB stars to remove the stellar envelopes, especially as the surface is enriched in C which may produce lots of dust. The low–Z AGB and massive stars may lose a large fraction of their mass.

These stellar winds produce very peculiar chemical enrichments of the early galaxies. The chemical composition of the rotationally enhanced winds of very low Z stars 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. 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 that are very similar to those observed in the C–rich, extremely metal–poor stars as shown by Meynet *et al.* (2006). Rotating AGB stars and rotating massive stars have about the same effects on the CNO enhancements. Nevertheless, abundances of s-process elements and the ^{12}C/^{13}C ratios could help us to distinguish between contributions from AGB and massive stars. As shown by Chiappini *et al.* (2006), these peculiar

enrichments remarkably well account for the initial chemical evolution of the C/O, N/O and O/Fe ratios in the Galaxy.

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Discussion

SANA: Thanks for this very nice summary. I have a comment rather than a question. I would like to warn against the use of García & Mermilliod (2001, *A&A*, 368, 122) on the O–star binary fraction, and particularly against the very large fraction (up to 80 %) proposed for some clusters. Several authors mainly from the Liege group (M. De Becker, G. Rauw) and myself, have reinvestigated the question and could not confirm the extreme binary fraction proposed for some clusters. Regarding Tr 14 for which you quote Penny *et al.* (1993, *PASP*, 105, 588) showing that none of the 9 stars are binaries, it is interesting to keep in mind that there is 2 good binary candidates: one of them is a RV–variable and the other shows NT radio emission. Though this needs to be confirmed, the binary fraction in Tr 14 might be significantly different from zero. I have proposed a poster revising the binary fraction in nearby clusters and my conclusion is that the current available data do not allow to prove that the O-stars binary fraction is varying from one cluster to another.

MAEDER: Thank you for these comments. Thus, you have presented your poster...

LEITHERER: Most the effects you discussed kick in only at really low Z. Observationally this makes many of these predictions hard to test in individual stars because the lowest oxygen abundance in the local universe is just a couple of %. Nevertheless, what can we learn from observations of individual stars in galaxies like I Zw 18?

MAEDER: I think the observations of individual stars in I Zw 18 is the next major step toward the direct observations of very low Z stars, i.e. toward the "First Stars". The large telescopes will open magnificent new possibilities. For now, we nevertheless have most useful infos from the chemical abundances in very low–Z halo stars and in globular cluster stars. Although these are low mass stars, their abundances provide direct information on the massive stars at very low Z.

VANBEVEREN: The Be components in X–ray binaries are probably formed via mass transfer during Roche lobe overflow. Accounting for the fact that a supernova explosion of one of the components of a binary, disrupts the binary, it can be expected that for every Be star in an X–ray binary there are 10 Be stars that are single but are formed via mass transfer as well. So, I do not understand how one can use Be–star statistics in order to defend the role of rotation on the evolution of single stars, by denying the binary formation mechanism for this type of stars.

MAEDER: Maybe you should notice that the issue was not the hypothetical binary formation of Be stars, but whether on the average rotation is higher at lower Z. In this respect, new results by Martayan *et al.* (poster, this volume) beautifully confirm the claim that I made in 1999 with Eva Grebel and J.C. Mermilliod (*A&A* 346, 459), i.e. that low Z stars have on the average a higher rotation.

LIMONGI: A comment on the primary N production in low Z stars. In non rotating models, primary N production is common because of the mixing between the H convective shell and the H rich envelope. Such a phenomenon is common and it was already recognized by Woosley and Weaver in 1982. But as soon as Z increases this phenomenon disappears. In rotating models, on the contrary, you can have primary N production also at higher metallicities.

MAEDER: I agree with your remarks. However, rotation enhances the primary N production. We get primary N production only for metallicities below that of the SMC.

André Maeder.

Part of the Local Organizing Committee resting at Waimea Canyon.
From left to right: Vivian U, Miguel Urbaneja, Laurie Clark and Fabio Bresolin.