

Modeling massive stars with rotation: the case of Nitrogen enrichments

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Abstract

Recently, the concept of rotational mixing has been challenged by some authors (e.g. Hunter et al. 2008). We show that the excess N/H is a multivariate function $f(M, \text{age}, v \sin i, \text{multiplicity}, Z)$. To find a correlation of a multivariate function with some parameter, it is evidently necessary to limit the range of the other involved parameters as much as possible. When this is done, the concept of rotational mixing is supported by the observations. We also show that the sample data are not free from several biases. A fraction of $\sim 20\%$ of the stars may escape to the relation as a result of binary evolution.

Introduction

In the late 70's, the reality of mass loss in massive stars was debated as well as its effect on the evolution. When this eventually became accepted (Chiosi & Maeder 1986), the next question was whether the large differences in the populations of massive stars (for example the WR/O and WN/WC star numbers) were due to differences in mass loss with metallicity Z . Today, the debate concerns the reality of rotational mixing and its effects on massive star evolution. History never reproduces itself similarly, nevertheless there is a great parallelism in these debates, which are normal steps in the progress of knowledge and finally lead to a better understanding of stellar physics and evolution.

There is an impressive list of consequences of stellar rotation (Maeder & Meynet 2000), many of which are supported by observations: about the stellar shape, the temperature distribution at the surface, the mass loss and its asymmetries, on the size of the cores, the tracks in the HR diagram, the lifetimes, the surface composition, the chemical yields, the ratios of the different kinds of massive stars (blue, red supergiants, WR stars), the types of supernovae and the remnant masses, etc. In this Liege Colloquium, the reality of the rotational mixing was disputed by several authors on the basis of new observations, in particular the VLT-Flames survey (Hunter et al. 2008). Thus, we concentrate here on this problem, firstly by recalling some theoretical predictions concerning surface enrichments and secondly by carefully examining the observations.

Recall of theoretical predictions concerning rotational mixing

In the mass range of ~ 10 to $20 M_{\odot}$ considered here, mass loss has a limited importance during the Main Sequence (MS) phase. The changes of abundances are expected to be mainly due to rotational mixing. The main effect producing element mixing is the diffusion by shear turbulence, which itself results from the internal Ω gradients built during evolution. To a smaller extent, meridional circulation makes some transport, however mainly of angular

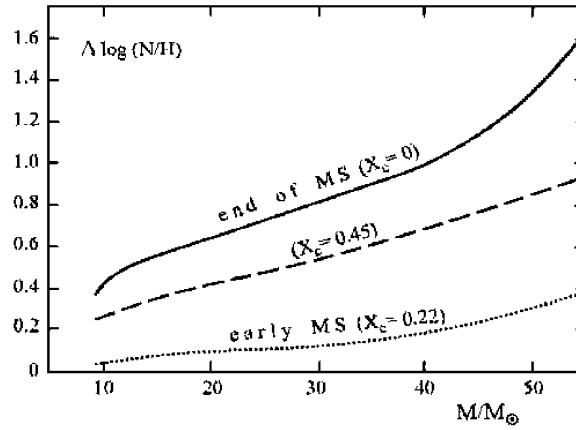


Figure 1: The differences in $\log(N/H)$ as a function of the initial masses at 3 stages during the MS phase for models with $Z = 0.02$ with average rotation velocities of 217, 209, 197, 183, 172, 168 km s^{-1} for respectively 12, 15, 20, 25 40 and 60 M_{\odot} . These 3 stages are indicated by the value of the central H-content X_c .

momentum. Mixing brings to the surface the products of CNO burning: mainly ^{14}N and ^{13}C enrichments, ^{12}C is depleted with limited ^4He enrichment and ^{16}O depletion.

Fig. 1 shows the predicted variations of $\log(N/H)$ during MS evolution as a function of the initial masses (Meynet & Maeder 2000). (N/H) is here the abundance ratio of N and H in numbers (the relative differences in mass and number are the same). Without rotational mixing, there would be no enrichment until the red supergiant stage. Rotation produces an increase (depending on velocity v) of N/H during the MS phase. The N excesses also depend on the ages t . The increase is modest during the first third of the MS phase, because the elements need some time to reach the surface, then it is more rapid. The N enrichments are larger for larger masses M . Thus we see that the N excesses are multivariate functions

$$\Delta \log(N/H) = f(M, t, v \sin i, \text{multiplicity}, Z). \quad (1)$$

Models with lower initial metallicities Z have higher N enrichments for given M and v (Maeder & Meynet 2001; Meynet et al. 2006). The excesses become very strong at metallicities Z as low as 10^{-8} .

Fig. 2 shows, for given M and Z , the evolution of the N excesses with age for different initial velocities. This figure shows that there can be no single relation between $v \sin i$ and the N/H excesses for a mixture of ages. The same is true for a mixture of different masses.

Binarity may also affect the N and He enrichments due to tidal mixing and mass transfer. A binary star with low rotation may have a high N/H due to tidal mixing or due to the transfer of the enriched envelope of a red giant. At the opposite, a binary star may also have a high $v \sin i$ and no N/H excess, in the case of the accretion of an unevolved envelope bringing a lot of angular momentum. A nice illustration has been given (Martins, 2009).

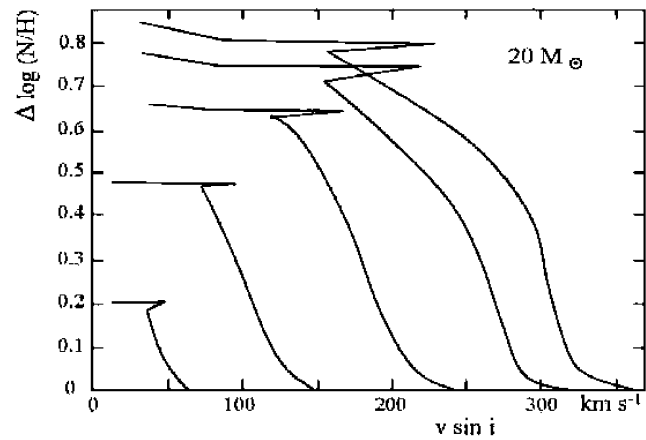


Figure 2: The evolution of the differences in $\log(N/H)$ during the MS phase as function of the actual rotation velocities ($\sin i$ being equal to 1 here) for models of $20 M_{\odot}$ with $Z = 0.02$ and different initial velocities.

Study of the observed N/H excesses

The M , age and Z dependences

Let us start by examining the mass, age and Z dependences of the N/H excesses. The data for different groups of stars with different Z are summarized in Table 1. In the Galaxy ($Z \approx 0.02$), the main recent data sources (Herrero 2003; Venn & Przybilla 2003; Lyubimkov et al. 2004; Huang & Gies 2006; Trundle et al. 2007) support significant excesses of He or of (N/H). In the lowest mass range studied ($6.6\text{--}8.2 M_{\odot}$), small excesses of He/H are still present (Lyubimkov et al. 2004). In the LMC ($Z \approx 0.008$), the excesses are larger (Hunter et al. 2007; Trundle et al. 2007). In the SMC ($Z \approx 0.004$), still much larger N excesses are observed (Venn, Przybilla 2003; Heap & Lanz 2006; Trundle et al. 2007; Hunter et al. 2007).

Table 1: The largest $\Delta \log(N/H)$ values observed for different types of stars in the Galaxy, LMC and SMC (differences in dex with respect to the local values in the considered galaxy). The average is equal to about the half of the indicated values.

Types of stars	$\Delta \log(N/H)$ Galaxy	$\Delta \log(N/H)$ LMC	$\Delta \log(N/H)$ 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

These data show the following facts, consistent with theoretical predictions:

- On the average, the N enrichments are larger for larger masses.

- The N enrichments are larger at lower Z .
- The He and N enrichments increase with the distance to the ZAMS (Huang & Geiss 2006). They are even larger in the giant and supergiant stages (Venn & Przybilla 2003). This property is also well observable for example in N11 (Fig. 34 of Hunter et al. 2007) and in NGC 2004 (Fig. 2 by Trundle et al. 2007).

The $v \sin i$ dependence of the N/H excesses

Several correlations of the N or He excesses with the observed $v \sin i$ have been performed. Huang and Gies (2006) and Lyubimkov et al. (2004) find a correlation of the He excesses with $v \sin i$ for B stars in the upper part of the MS band in agreement with model predictions.

In other comparisons (Hunter et al. 2008; Langer, this meeting; Brott, 2009), the authors conclude that "the observation ... challenges the concept of rotational mixing". They claim that "two groups of core hydrogen burning stars ... stand out as being in conflict with the evolutionary models". Group I contains rapid rotators with little chemical mixing, while Group II consists of low rotators with large N enrichments. We clearly disagree with the conclusions of Hunter et al. (2008), which mainly result from the fact that, instead of Eqn. (1), their analysis implicitly assumes that

$$\Delta \log(N/H) = f(v \sin i) . \quad (2)$$

We note the following points:

- Their sample contains a mixture of stars in the mass interval of 10 to 30 M_{\odot} . Fig. 1 shows that over this mass interval, the N/H excesses vary as much as by a factor of two for a given rotation velocity.
- The sample by Hunter et al. consists of stars in extended regions around the LMC clusters N11 and NGC 2004. As stated by the authors, their sample also contains field stars, which do not necessarily have the same age or degree of evolution as the cluster stars. Thus, *large differences of N/H are possible for given M and v sin i*. Also, the two clusters do not have the same ages, N11 being younger than NGC 2004, so that the stars near the turnoff of N11 have a mass of about 20 M_{\odot} , while this is about 14 M_{\odot} for NGC 2004 according to the HR diagrams by respectively Hunter et al. (2007) and Trundle et al. (2007).
- The completeness of the binary search is unknown.

To limit the severe effects of mass and age differences, we consider the two clusters separately. In N11, we limit the sample to the stars in the mass range 14 to 20 M_{\odot} on the basis of the data provided by Hunter (2008) and in the formal MS band as given by Fig. 34 from Hunter et al. (2007). In NGC 2004, we take the mass interval 13 to 16 M_{\odot} (same source) and in the formal MS band from Fig. 2 by Trundle et al. (2007). Figs. 3 and 4 show the results. Ideally these mass intervals should even be smaller.

For N11, we see that Group I (stars with high $v \sin i$ and low N/H) has essentially disappeared. There remain only 2 evolved binary stars, which is consistent with some scenarios of binary evolution. We suspect that Group I was also largely formed by stars of smaller ages and/or lower mass stars, where for a given $v \sin i$ the N excesses are smaller. A support to the latter possibility comes from the fact that the average mass of the stars in the region of Group I is 12.8 M_{\odot} (for $v \sin i > 180 \text{ km s}^{-1}$ and $12 + \log(N/H) < 7.30$) and 17.1 M_{\odot} for stars with $v \sin i > 180 \text{ km s}^{-1}$ and $12 + \log(N/H) > 7.30$. Group II is mainly made from evolved stars (open circles), which explains the low velocities and high N abundances. The two remaining stars in this group can easily be stars with a small $\sin i$, especially more than

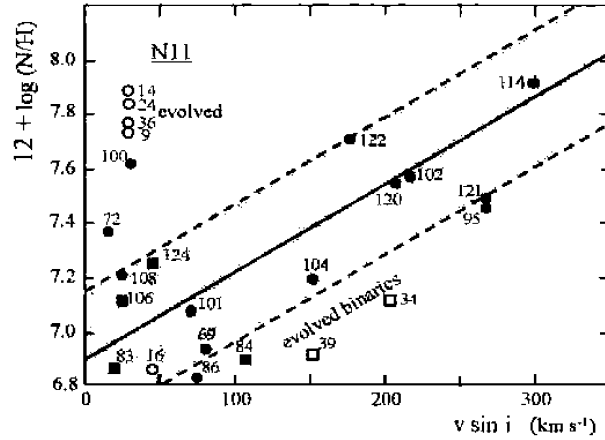


Figure 3: The N abundance (in a scale where $\log H = 12.0$) as a function of $v \sin i$ for the MS stars (black dots) in N11 with masses between 14 and 20 M_{\odot} according to Hunter (2008). The binaries are shown by a square. The evolved stars in a band of 0.1 dex in $\log T_{\text{eff}}$ beyond the end of the MS are shown with open symbols. The gray band indicates uncertainties of ± 0.25 dex.

the sample data by Hunter et al. (2008) is largely biased toward low rotators. The ratio of star numbers with $v \sin i \geq 250 \text{ km s}^{-1}$ to those with $v \sin i \leq 100 \text{ km s}^{-1}$ is 0.14, while in the clusters studied by Huang & Gies (2006), this ratio amounts to 0.40! Thus, the sample by Hunter et al. contains a large excess of slow rotators. We conclude that the bulk of stars in N11 shows a relation of the excess of N/H depending on $v \sin i$ (the mean square root of the data for the MS band stars is 0.23 dex from the data by Hunter (2008), the scatter in $v \sin i$ is not given). The amplitude of the (N/H) is about 0.6 dex for velocities of 200 km s^{-1} , slightly higher than at the corresponding mass in Fig. 1 for $Z = 0.02$.

For NGC 2004, the results are essentially similar. For most stars there is a relation between the excess of N/H and $v \sin i$. For Group I, there remains only star nb. 100 (which is not much for a group). This star is interesting. Its mass is 13 M_{\odot} , $v \sin i$ is 323 km s^{-1} , the highest of the whole sample. In reality, the velocity is still higher because the authors do not account for gravity darkening (Fig. 4 of Hunter et al. (2008) tends to support this remark). This star might be a reaccelerated binary or simply a younger star in the field. Another possibility (which we favour) is that its parameters have been incorrectly appreciated due to the extreme rotation. In this respect, a $\log g$ vs. $\log T_{\text{eff}}$ diagram, e.g. Fig. 16 by Meynet & Maeder (2000), shows that a too high mass is assigned to a fast rotating star if in the $\log g$ vs. $\log T_{\text{eff}}$ diagram its mass is determined from nonrotating models. Thus, the mass of star nb. 100 could be lower than 13 M_{\odot} which is the lower bound of our sample. To know whether this is what occurred for this star, the whole reduction process should be redone. For Group II, a large fraction consists as for N11 of evolved stars. Again for NGC 2004, the N enrichments increase with $v \sin i$ in agreement with theory.

We also note that the data used in the analysis by Hunter et al. (2008) are subject to several biases. Firstly, the sample contains no Be stars, while their number fraction is about 15 to 20 % in the LMC. This contributes to bias the sample toward low velocities. A second source of bias is that the $v \sin i$ determinations are based on models assuming that the stars

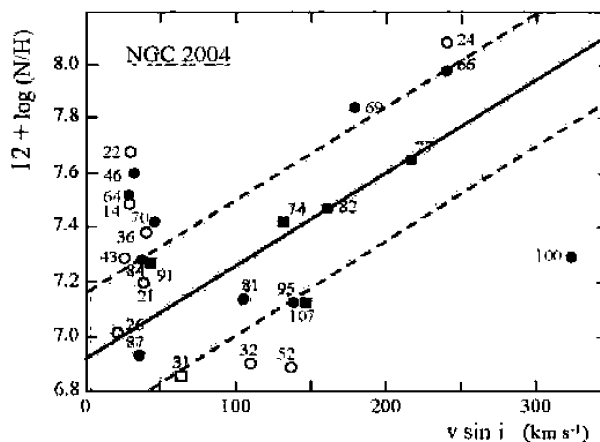


Figure 4: The N abundance as a function of $v \sin i$ for the MS stars in NGC 2004 with masses between 13 and 16 M_{\odot} . Same remarks as for Fig. 3.

are uniformly bright, with no account given to gravity darkening (now an observed effect). Thirdly, in the values of gravity used to estimate the masses, no account is given to the gravity change due to rotation. The effects of evolution and rotation should be disentangled before any mass is assigned.

Conclusions

To find a correlation for a multivariate function like N/H with some parameter like $v \sin i$, it is necessary to limit the range of the other involved parameters as much as possible. Otherwise, the conclusions may be erroneous. We note that data samples limited in mass and ages support an N enrichment depending on rotational velocities. Stars beyond the end of the MS phase do not obey to such a relation, because their velocities converge toward low values (see Fig. 12 by Meynet and Maeder 2000). A fraction, which we estimate to be $\sim 20\%$ of the stars, may escape from the relation as a result of binary evolution, either by tidal mixing or mass transfer.

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DISCUSSION

Noels: Since the enrichment in CNO is strongly sensitive on the metallicity, I am wondering if it is correct to use the solar CNO/Fe ratio to compute models of “new born” massive stars in a low Z environment.

Maeder: At lower Z, the models composition accounts for the enhanced α -elements (C, O, Ne, Mg, Si, ...). When there is a primary N production for $Z < 10^{-3}$, the amount of new N produced is independent on the initial abundances.

Noels: In models computed with rotation, is there still an intermediate convective zone?

Maeder: This is an interesting point. Rotational mixing brings He in the region of the H-burning shell, which thus becomes weaker and this also weakens or makes the intermediate convective zone to disappear. The disappearance of the intermediate convective zone in turn allows the star to become a red supergiant. Thus, rotational mixing strongly affects (in a positive way) the blue to red supergiant ratio.

Cantiello: You stressed the importance of the Gratton-Öpik term for the angular momentum transport in rotating massive stars. How reliable is the existence of Gratton-Öpik cell in a baroclinic star, i.e. a star where horizontal turbulence is strong (allowing for shellular approximation)? In particular, wouldn't the topology of the circulation be changed dramatically by such horizontal turbulence?

Maeder: The horizontal turbulence strongly affects the transport of chemical elements by meridional circulation. I refer you to the important study by Chaboyer & Zahn (1992) on this subject. The effect on the transport of angular momentum is likely small.

Aerts: Let us suppose that we have a seismic constraint from rotationally splitted detected frequency multiplets and we prove the rotation to be rigid and very slow everywhere in the star. If, in this case, the modeling requires an overshooting parameter $\alpha_{ov} \neq 0$, can we ascribe this to convective overshoot only, or are there still other effects that may cause an extent of the core?

Maeder: In case of solid body rotation, many instabilities (shears, baroclinic instabilities) are not present. However, the meridional circulation and its associated transport is still there, in addition to a certain amount of overshooting. This is interesting in the sense that it can allow to already possibly discriminate between certain effects.

Baglin: Coming back to the case raised by Conny Aerts, I would like to repeat that we will soon be able to measure the core rotation rate and the extent of the mixed region through seismology. Can we distinguish between overshooting and extension due to rotation?

Maeder: I think the answer will be yes, because the slope of the μ -gradient outside the core is different in the two cases. I expect a milder slope in the case of rotational mixing compared to overshooting.

Baglin: What is the present accuracy on the stellar structure of a massive star for which we assume that we have very precise fundamental parameters from observations?

Maeder: The basic structure of a massive star is simpler than the solar structure in some respects : simpler opacities, no large non-adiabatic convective layers. In other respects it is more complicated, in particular with mass loss and mixing. However, for a given physics, the models by the various authors agree well.