A Massive Star Odyssey, from Main Sequence to Supernova
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Rotating stellar interior models at $Z = 10^{-5}$ and CNO yields for early galactic evolution

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Abstract. We calculate a grid of star models with and without the effects of axial rotation for stars in the mass range between 2 and 60 $M_{\odot}$ for the metallicity $Z = 10^{-5}$. We find that in these models primary nitrogen is produced during the He-burning phase by rotational diffusion of ^{12}C into the H-burning shell. The intermediate mass stars of very low Z are the main producers of primary ^{14}N, but massive stars also contribute to this production; no significant primary nitrogen is made in models at metallicity $Z = 0.004$ or above. We calculate the chemical yields in He, C, N, O and heavy elements and discuss the chemical evolution of the CNO elements at very low Z. Remarkably, the C/O *vs.* O/H diagram is mainly sensitive to the interval of stellar masses, while the N/O *vs.* O/H diagram is mainly sensitive to the average rotation of the stars contributing to the element synthesis.

1. Introduction

What is the impact of rotation on the yields of helium, metals, ^{12}C, ^{14}N and ^{16}O at very low metallicity? To answer this question we have computed rotating models at the metallicity $Z/Z_{\odot} = 1/2000$. The physics included in the present rotating models is the same as in Maeder & Meynet (2001, see also Maeder & Meynet, these Proceeedings). These models can account for the observed surface enrichments (Meynet & Maeder 2000) and for the observed number of red supergiants in the Small Magellanic Cloud (Maeder & Meynet 2001)

A more detailed discussion of the models at $Z = 10^{-5}$ is given in Meynet & Maeder (2002a). A first discussion of the question of the primary nitrogen production in these models can be found in Meynet & Maeder (2002b). Let us just recall here that rotation modifies the way stars are loosing mass (Maeder 1999; Maeder & Meynet 2000), enlarges the convective cores and induces mixing processes in radiative zones (Maeder & Zahn 1998).

We consider here the cases of initial masses between 2 and 60 $M_{\odot}$. For the rotating models, we adopt values for the initial rotational velocities such that the average rotational velocity during the MS is of the order of about 230 km s^{-1} not far from the mean rotational velocity observed for main sequence OB stars at solar metallicity. Let us note here that one does not know whether the initial distribution of the rotational velocities varies as a function of the metallicity. In case the fraction of fast rotators would increase for lower metallicites, as suggested by some observations (see Maeder *et al.* 1999), the effects presented below, in particular the production of primary nitrogen, would be stronger.

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2. Effect of the stellar winds in rotating models

At the very low metallicity considered here, the mass removed by the stellar winds is negligible for the non-rotating models. Typically the non-rotating $60\,M_\odot$ has lost less than 1% of its initial mass at the end of the carbon burning phase. On the other hand, the rotating $60\,M_\odot$ model at the same stage has lost more than 16% of its initial mass.

Let us recall here that the enhancement factor of the mass loss rates due to rotation increases when the surface angular velocity Ω approaches the surface break-up angular velocity. Interestingly, at low metallicity, since less angular momentum is removed at the surface by stellar winds, a star with a given initial rotation has more chance to reach the break-up limit. This becomes particularly true for the high mass stars which, at a given metallicity, present more rapid meridional currents in the outer layers than the low mass stars (see Maeder & Meynet 2001). These outwards currents transport angular momentum from inside to the outer regions of the star and thus accelerate the outer zones, which may thus reach break-up velocities. Let us note that this has interesting consequences in particular for zero metallicity stars. Even if the loss of matter through radiative driven winds is very small (see Kudritzki, these Proceedings), these stars may lose a great quantity of mass when they encounter the break up limit (see Marigo, these Proceedings).

In the case of our rotating $60\,M_\odot$ model at $Z=10^{-5}$, this enhancement of the mass loss rates has a non negligible impact on the yields in nitrogen. Indeed more than half of the new synthetized nitrogen produced by the star is ejected into the interstellar medium by the stellar winds. The effect of mass loss would still be greater for stars with higher initial masses.

3. Consequences of the larger CO cores in rotating models

The masses of the CO cores at the end of the carbon-burning phase are bigger in the rotating models, by 16% in the 20 $M_\odot$ star and by 42% in the $60\,M_\odot$ model. As a consequence the yields in carbon and oxygen are enhanced by rotation (Heger *et al.* 2000; Meynet & Maeder 2002a). Comparing the integrated yields from a stellar generation obtained from the rotating and the non-rotating models, one obtains, with a Salpeter's IMF slope, that the carbon yields are increased by about 28% and the oxygen yields by 35%. Let us recall here that the initial mass range considered lies between 2 and $60\,M_\odot$ and that we do not account for the possibility, when a black hole is formed, that all the ejected matter may be swallowed by the black hole (Maeder 1992).

4. Effect of rotationally induced mixing in the radiative zones

4.1. The great efficiency of rotational mixing at low Z

The most important effects at low metallicity are the mixing processes induced by rotation in the radiative zones. These effects are responsible for the surface enrichments and they deeply affect the yields in nitrogen as we shall see. To illustrate this point, Figure 1 (left panel) presents the evolution of the N/C ratio at the surface of stars of different initial masses, rotational velocities and metallicities. The most striking effects are on one side the enhancements obtained at the surface of the rotating stars already during the main sequence and, on the

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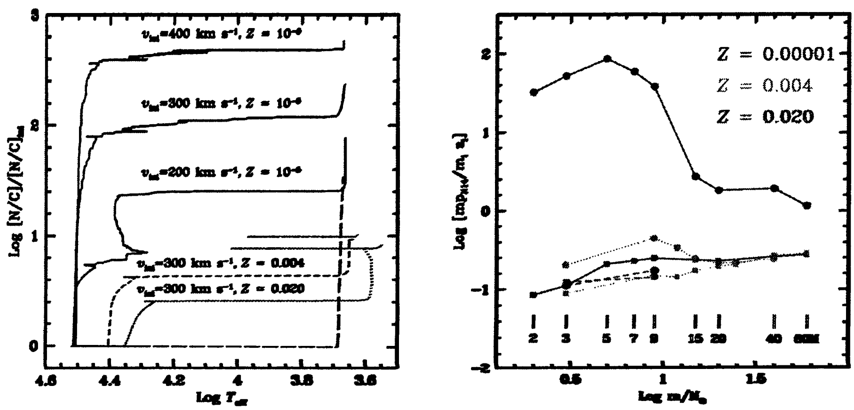

Figure 1. *Left:* Evolution as a function of $\log T_{\rm eff}$ of the surface abundance ratio N/C. The abundance ratios are normalized to their initial value. The tracks are for $9\,M_\odot$ at $Z = 10^{-5}$ with different initial rotational velocities. The long-dashed line corresponds to a non-rotating $9\,M_\odot$ stellar model at $Z = 10^{-5}$. The dotted and the short-dashed lines show the evolutions of rotating $9\,M_\odot$ models at $Z_\odot$ and at $Z = 4\times10^{-3}$, respectively ($v_{\rm ini} = 300\,{\rm km\,s^{-1}}$). *Right:* stellar yields of ^{14}N for different stellar masses, metallicities and rotational velocities. Yields are expressed as a fraction of the total initial content in heavy elements.

other side, the increase of these enhancements for lower Z models. Why do we have stronger enhancements at lower metallicities? Firstly, whatever the metallicity, the chemical species are mainly mixed through shear diffusion, while the angular momentum is mainly transported by meridional currents. In the outer layers the velocity of the meridional currents, which bring angular momentum from inside to the outer parts of the star, decreases when the density increases (this is due to the Gratton-Öpik term). Thus at lower metallicities, since the stars are more compact, less angular momentum is transported outwards and the Ω-gradients are steeper. As a consequence, the shear mixing of the chemical species is enhanced. This explains why, as shown in Figure 1, the change of the surface abundances becomes more and more important for lower metallicities.

Is there any observational support to this theoretical result? There are at least some indications that this may be correct. One indication is the very interesting observation by Venn (1999) that the maximum nitrogen enrichments observed at the surface of A-type supergiants of the SMC are about three times the maximum enrichment observed at the surface of galactic A-type stars (see a more complete discussion in Maeder & Meynet 2001).

Another effect tends to reinforce the mixing of the chemical elements at low Z. Indeed, when the metallicity decreases, the stars are more compact, thus the timescale for mixing is smaller, since it scales as $R^2/D_{\rm shear}$, where $D_{\rm shear}$ is the diffusion coefficient and R the radius.

4.2. Consequences for primary nitrogen production

An important consequence of this efficient rotational mixing at low Z is the production of primary nitrogen, as can be seen in Figure 1 (right). In this figure the yields in ^{14}N are given as a fraction of the initial content in heavy elements. If nitrogen is produced by a secondary process, *i.e.*, from the carbon and oxygen initially present in the star, only a fraction of the metals can be converted into nitrogen through the CNO cycle and the yields expressed as a fraction of the heavy elements content are inferior to one (; this does not necessarily mean that when the yields expressed as a fraction of the initial metal content are inferior to one, no primary nitrogen is produced. We simply say here that a secondary production necessarily implies that the yields so defined are inferior to one). When the yields are orders of magnitudes greater than the initial content in metals, necessarily most of the nitrogen produced has a primary origin, *i.e.*, it comes from the transformation of carbon and oxygen produced by the star itself in the helium-burning zone. We see that this is what happens in our rotating models at $Z = 10^{-5}$. This primary nitrogen is mainly produced during the core helium burning phase. The carbon and to a less extent the oxygen produced in the He-core diffuse in the H-burning shell where they are transformed into nitrogen through the CNO cycle. This is a different mechanism than the one usually proposed in the literature, namely the hot bottom burning. In this last mechanism, primary nitrogen is produced at the bottom of the convective envelope of AGB stars having undergone the third dredge-up (see the yields by Marigo 2001; van den Hoek & Gronewegen 1997).

From Figure 1 (right panel), we also see that the most important contributors are the intermediate mass stars, although the process of primary nitrogen production described above is realized in the whole mass range studied here. Thus these rotating models would be consistent with some time lag between the release of oxygen and that of nitrogen (Edmunds & Pagel 1978; Henry *et al.* 2000). In this respect, it is interesting to mention that the effect of rotation on the MS lifetime is different at different metallicity. At solar metallicity, the MS lifetimes are increased while at very low metallicity, most of the stars have their MS lifetimes reduced by rotation. The reason for this is explained in Meynet & Maeder (2002) to which the reader can refer for more details. A consequence of this feature is that the time lag between the release of the new synthesized products by massive stars and the enrichment due to the intermediate mass star is reduced. As a numerical example, between the release by a rotating $60\,M_\odot$ star and by a rotating $3\,M_\odot$ star, there are about 440 Myr at solar metallicity. At $Z = 10^{-5}$, this time lag is reduced to 270 Myr. At the metallicity of the SMC and at solar metallicity, very little or no primary nitrogen is produced. This is a consequence of the less efficient mixing induced by rotation at higher Z.

In Meynet & Maeder (2002a) we have used the yields of the rotating and the non-rotating models in a very simple chemical evolution model. The two main results are the following. First the quantities of primary nitrogen produced by the new mechanism proposed here are significant. We obtained that it can account for about half the value of the plateau level of the N/O ratio at low Z (see *e.g.*, Henry *et al.* 2000). Accounting for the facts that oxygen can be locked in dust, in black holes or expelled from the galaxy by SNe driven superwinds, this is a quite encouraging result. Secondly we obtained that the evolution of the C/O ratio as a function of O/H is not much dependent on rotation, but is quite dependent on the mass range responsible for the chemical enrichment. Together with the N/O *vs.* O/H plane, this diagram can be used to disentangle both the effects of rotation and those due to the mass range.

5. Conclusion

Rotation, as accounted for in the present models, naturally leads to primary nitrogen production at low metallicity. This production does not result from any fine tuning of the input parameters of the models, but is a consequence of the higher efficiency of the rotational mixing at low Z.

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Discussion

Heger: Could the floor value of $^{14}N/^{18}O$ be made by binaries?

MEYNET: What I have shown is that for rotating stars at $Z=10^{-5}$, primary nitrogen is synthesized during the core He-burning phase. This process would also occur if the star belongs to a binary system. How it will be perturbed by tidal mixing, mass transfer, I do not know and it would be of course very interesting to study this point.

MATTEUCCI: This is more a comment than a question. The diagram you showed about N/O *vs.* O/H refers to many different objects (extragalactic H II regions, blue compact galaxies) and it is not useful to test the primary/secondary nature of nitrogen. The reason is simple: the plateau objects are galaxies which have formed stars even for long periods and there is no certainty that they show the signature of massive stars. (Some of them show solar α/Fe ratio!) You should refer to the N/O *vs.* O/H plot in the solar neighborhood, that is, in fact, a real evolutionary diagram.

LANGER: You describe a new mechanism to produce primary N in low-Z intermediate mass stars. Such stars are also supposed to form primary N at the TP-AGB stage due to hot bottom burning. How do the efficiencies of these two mechanisms compare?

MEYNET: The two mechanisms, primary ^{14}N production by HBB and by rotationally induced mixing, may contribute both. For the range of masses, from 2 to 60 $M_{\odot}$, and for an average rotational velocity on the MS of $\sim 230\,km\,s^{-1}$, rotational mixing alone leads to a N/O ratio which is about a factor of two below the plateau level ($\log N/O \simeq -1.6$.). Now, of course besides the possibility that HBB may also contribute, other effects can intervene, as O ejected by galactic winds, locked in dust or in black holes.

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