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The advanced phases of massive stars and the explosive yields

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Abstract. I will briefly review the dependence of the explosive yields on the initial mass, metallicity and initial rotational velocity.

Keywords. Stars: evolution, Stars: interiors, Stars: rotation, Stars: Supernovae, Stars: abundances

1. Introduction

Massive stars play an active and fundamental role in both the physical and chemical evolution of the Galaxies. Among the others, they strongly contribute to the progressive enrichment of the interstellar gas in elements with $Z >= 2$. In particular they dominate the production of the intermediate elements O to Ca, contribute to the synthesis of C, of the Fe-peak nuclei (Sc to Zn) and of the S-weak component (Ga to Zr). Viceversa these stars are not supposed to be primary producers of N, F and the main S component. In some specific cases, like at $Z = 0$, a consistent amount of N may be produced as a consequence of the penetration of the He convective shell in the H rich mantle.

The amount of matter synthesized by each star depends on its initial mass, chemical composition and rotational velocity. In the following we will briefly present our latest grid of models and associated explosive yields. The code will be presented in Sec. 2 while the new yields will be briefly discussed in Sec. 3.

2. The FRANEC code

All present models have been computed with the latest version of the FRANEC evolutionary code whose latest release has been described in Chieffi & Limongi (2013) and references therein. This version of the code includes the effects of rotation and takes into account two instabilities: meridional circulation and shear. The adopted nuclear network extends from H to Bi and follows explicitly the temporal evolution of 335 nuclear species. We added in these computations an additional mass loss when the luminosity exceeds the Eddington one: in particular we assumed that all the mass zones where $L/L_{\rm edd} \geqslant 1$ are instantaneously lost from the star. The adopted solar chemical composition is the

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Table 1. Elements assumed to be overabundant at metallicities lower than solar. The overabundances where determined according to Cayrel *et al.* (2004) and Spite *et al.* (2005)

overabundance		
[C/Fe]	=	0.18
[O/Fe]	=	0.47
[Mg/Fe]	=	0.27
[Si/Fe]	=	0.37
[S/Fe]	=	0.35
[Ar/Fe]	=	0.35
[Ca/Fe]	=	0.33
[Ti/Fe]	=	0.23

Asplund *et al.* (2009) one. At lower initial Fe abundances, i.e. [Fe/H] $= -1, -2$ and -3, some elements are assumed to be overabundant with respect to the solar value, see Table 1. The global metallicities therefore are $Z = 1.345 \cdot 10^{-2}$, $3.236 \cdot 10^{-3}$, $3.236 \cdot 10^{-4}$ and $3.236 \cdot 10^{-5}$ The corresponding adopted initial He abundances are $Y = 0.265$ ([Fe/H]=0), $Y = 0.25$ ([Fe/H]=-1) and $Y = 0.24$ for the two lowest ones.

3. The grid of models and the yields

We computed a grid of models extending in mass between 13 and 80 $M_\odot$ (13, 15, 20, 25, 30, 40, 60 and 80), in metallicity between [Fe/H]=0 and [Fe/H]=-3 (0, -1, -2 and -3) and for three initial equatorial rotational velocities $v = 0$, 150 and 300 km/s. All models where followed from the Hayashi track up to the moment of the core collapse. Figs. 1 and 2 show the logarithm of the net yields in solar masses of the elements included in the network as a function of the initial mass for solar metallicity models. Figs. 3 and 4 show the same quantities for [Fe/H] $= -2$. In all Figures, the black lines refer to non rotating models while the red one to models initially rotating at 300 km/s.

The first thing worth noting in Figs. 1 to 4 is that on average the elemental yields tend to increase with the initial mass at all metallicities. This is true for both the elements produced in the hydrostatic and the explosive burnings. The basic reason is that the convective mixing control both the amount of matter processed by a given burning and the final mass-radius relation. Since the sizes of the convective cores in central H and He burnings and the C convective shells usually scale directly with the initial mass (at least until the mass loss is not so efficient to reduce significantly the He core mass), the amount of mass processed by the H, He and C burnings increases with the initial mass and therefore the products of these burnings as well. In addition to this, since the size of the H convective core determines also the mass of the He core, which in turn controls the final compactness of the star at the moment of the core bounce, also the final mass-radius relation is largely controlled by the extension of the H convective core. Since the amount of mass processed by the explosive burnings scales directly with the final mass-radius relation, it follows that also the yields of the elements produced in the explosive burnings basically increase with the initial mass of a star. It goes without saying that, given the pivotal role of mixing in the synthesis of many elements, any modification of the border of the unstable areas or the details of the mixing could significantly affect the final yields of many elements. By the way it is clear that we are not considering here the main s-component which is basically synthesized in a radiative environment within the ^{13}C pocket in stars of 1 to 3 $M_\odot$ (Straniero *et al.* 1995) as well as the nuclei produced by the r-processes.

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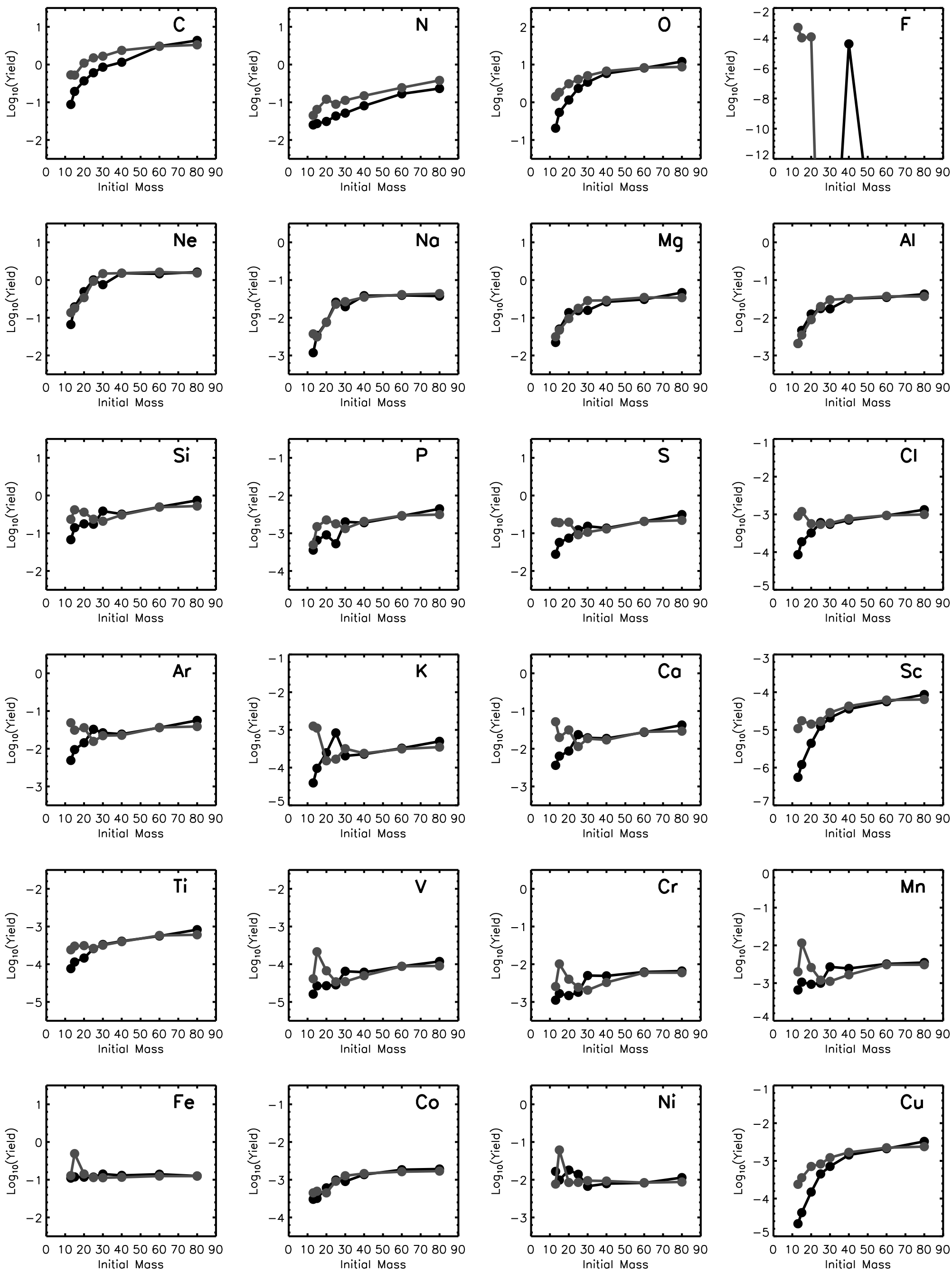

Figure 1. See text.

Since the main effect of rotation is that of favoring an additional mixing that sums to that of the classical thermal instabilities, we can expect that in general the effect of rotation will be that of increasing the yields of the elements. Before proceeding further, it is however important to stress that the amount of mixing induced by the rotational instabilities obviously scales directly with the adopted initial rotational velocity: the

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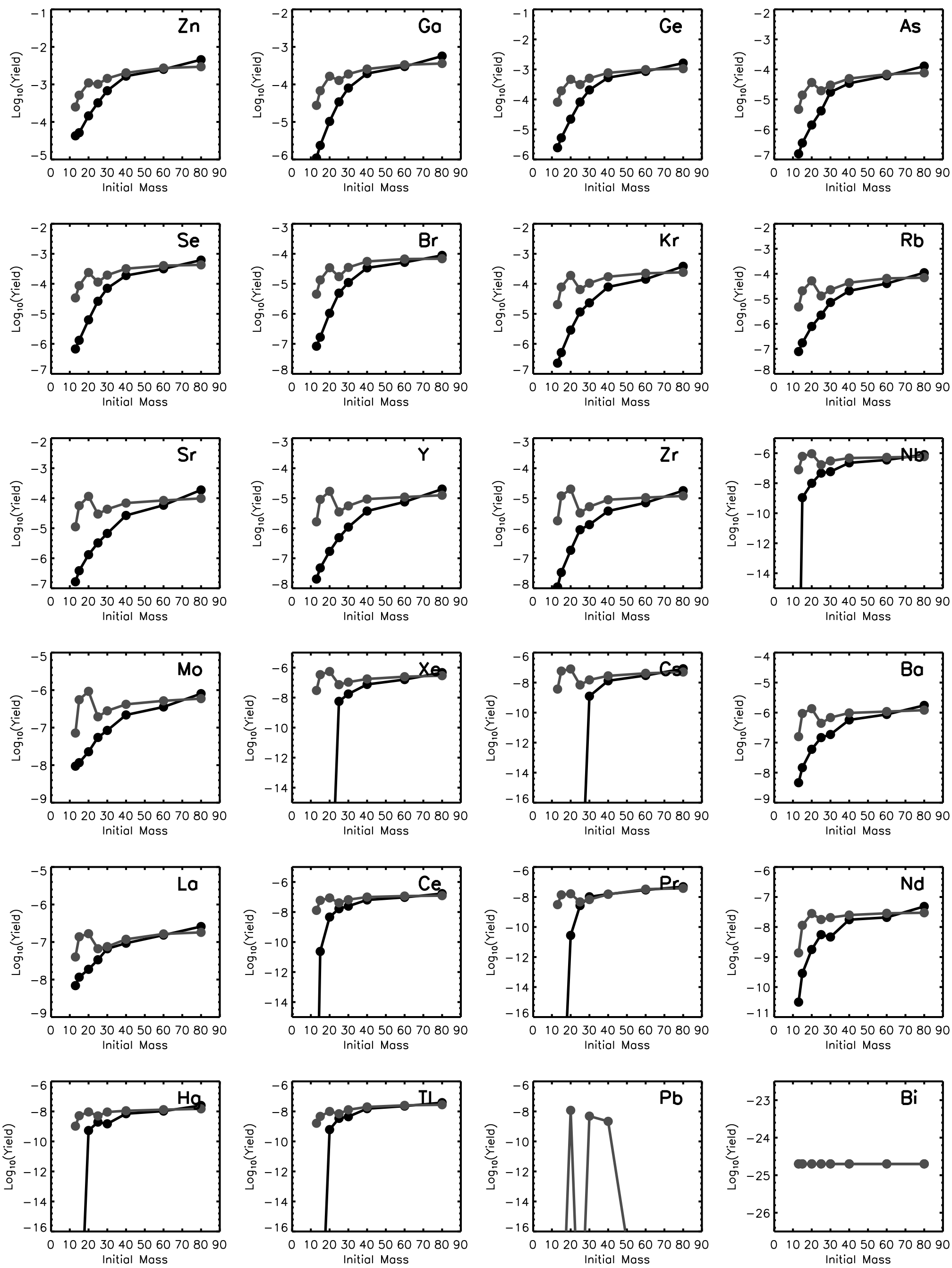

Figure 2. See text.

larger the initial velocity the stronger the effect of the mixing. For sufficiently large initial velocities, the stars can be even forced to be fully mixed and follow an homogeneous evolution (Brott *et al.* 2011) qualitatively similar to that of very low mass stars (0.5 $M_\odot$ or less) that are fully convective in central H burning. For the specific initial rotational velocities chosen here, the influence of rotation on the yields is not very strong, the

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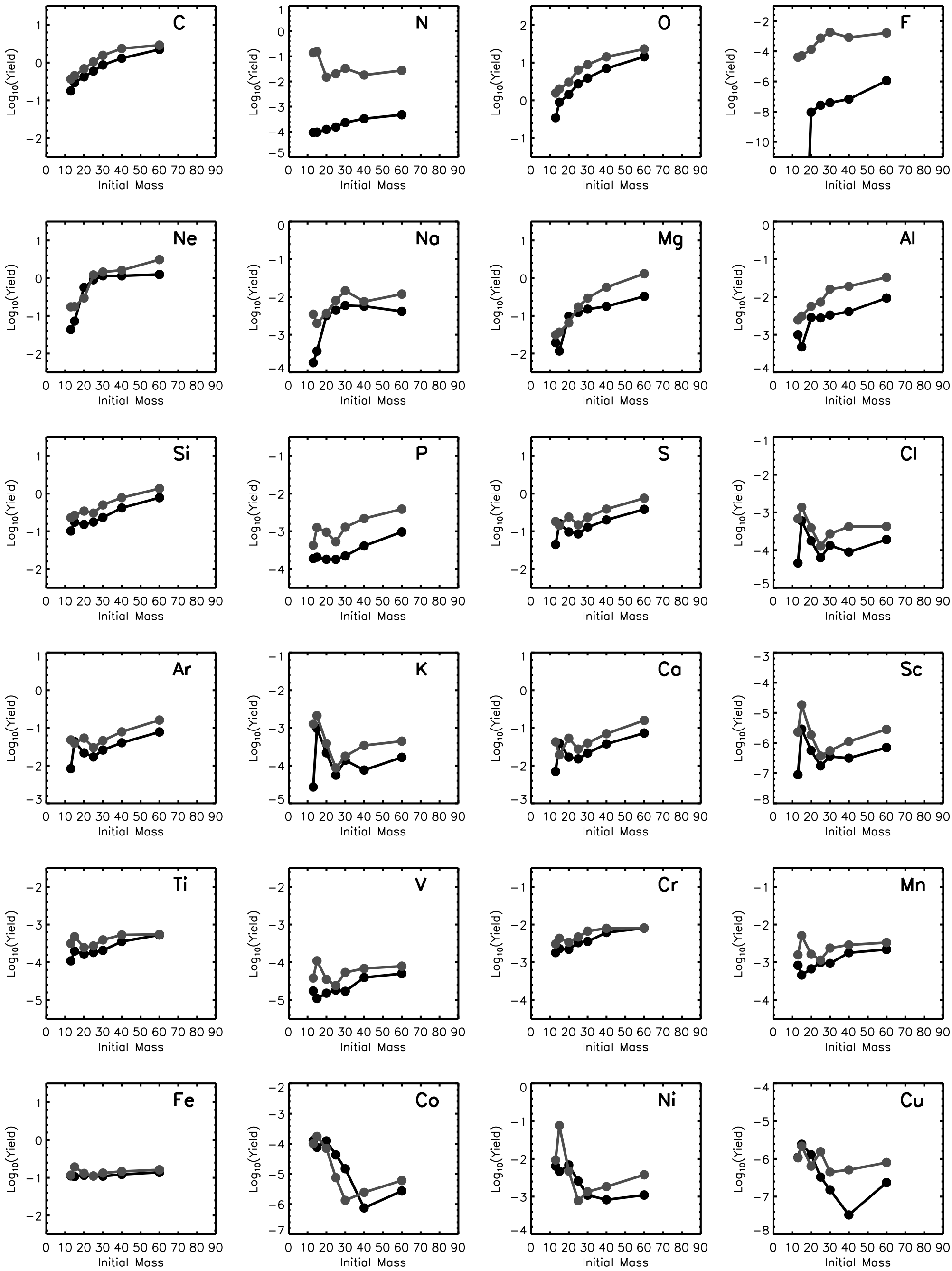

Figure 3. See text.

largest differences occurring for F and the s-process elements in the sense that rotating models tend to increase significantly the yields of these elements. As we turn to lower metallicities, this effect becomes much stronger, so that at [Fe/H] = −2, for example, F and all the s-process elements are largely overproduced with respect to their respective non rotating model. Also N is largely overproduced by rotating models at sub solar Fe

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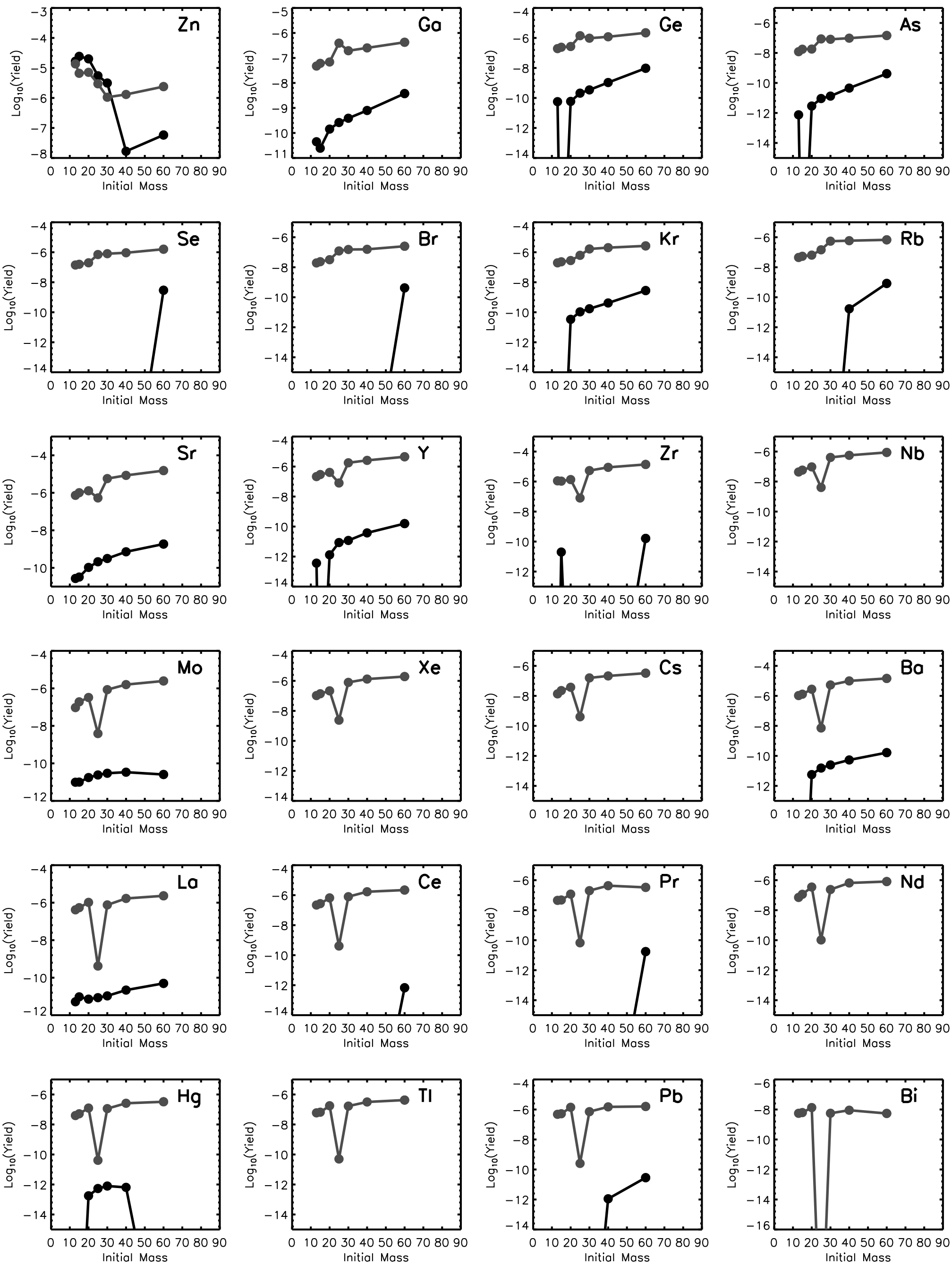

Figure 4. See text.

abundances. We will discuss in detail all such differences in a forthcoming paper. Here, as an example, we will focus only on Fluorine.

In massive stars F production occurs in the He convective shell that forms after the central He burning in the H exhausted core, above the outer edge of the He convective core. It is produced by the sequence $^{14}N(\alpha,\gamma)^{18}F(\beta+)^{18}O(p,\alpha)^{15}N(\alpha,\gamma)^{19}F$ (Goriely

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et al. 1989; Lugaro *et al.* 2004). The protons necessary to activate this sequence are produced by the ^{14}N(n,p)^{14}C nuclear reaction that activates also an additional source of ^{18}O through the ^{14}C$(\alpha,\gamma)^{18}$O. The neutron flux may be produced in principle by either the ^{13}C$(\alpha,n)^{16}$O and/or the ^{22}Ne$(\alpha,n)^{25}$Mg. The nuclear sequence sketched above implies that the key, basic fuel for the F production is ^{14}N because it may be either the source of the protons and/or of the neutrons through the ^{22}Ne channel. However, in standard non rotating models ^{14}N and ^{22}Ne cannot be present simultaneously because, as it is well known, the second one is produced by the burning of the first one. The ^{13}C channel, on the other hand, cannot be efficient because of the low ^{13}C equilibrium abundance left by the CNO cycle in the He core. The only minor production may occur when the He convective shell, after having converted all the ^{14}N in ^{22}Ne, advances in mass engulfing fresh ^{14}N from the radiative region above it. It goes without saying that this minor production is in any case possible only if the temperature in the He convective shell reaches at least 300 MK. This explains why F is basically destroyed or at most slightly overproduced in massive stars at all (non zero) metallicities. This scenario changes drastically in presence of rotation because of the continuous slow mixing of matter between the He convective core and the active H burning shell. In particular, freshly produced ^{12}C is continuously brought from the convective core up to the tail of the H burning shell where it is converted in ^{13}C and ^{14}N by the CNO cycle and then spread out within the He core. Vice versa the fresh ^{14}N brought back in the He convective core is quickly converted in ^{22}Ne and spread out again outside the convective core. The net result is that at the end of the central He burning the abundances of ^{13}C , ^{14}N and ^{22}Ne are all largely enhanced in the He core with respect to the non rotating models. In stars less massive than $25M_{\odot}$it is the higher concentration of ^{13}C responsible for the large and systematic F production. As the initial mass increases the temperature at the base of the convective shell increases as well so that the ^{22}Ne neutron source becomes progressively more important.

All what has been described above does not take into account the fundamental role played by mass loss in the synthesis of F. While the F net yield increases with the initial mass of the star at [Fe/H] $= -2$ (see Fig. 3) in both the rotating and non rotating models, at solar metallicity F is destroyed in the rotating models (for masses larger that $20\,M_{\odot}$) as well as in the non rotating ones (see Fig. 1). The reason is that, while at [Fe/H] $= -2$ mass loss does not fully remove the H mantle before the end of the central He burning, at solar metallicity mass loss is so efficient that it removes the whole H rich mantle (and part of the He core as well) well before the central He exhaustion, strongly inhibiting the interplay between the central He burning and the H shell that is necessary to raise the abundances of the key elements necessary to F production. By the way, the peak corresponding to the $40\,M_{\odot}$ non rotating star visible in Fig. 1 is an artifact due to the fact that this is the only non rotating model that does not destroy F, i.e. for which the net yield is not negative but just slightly positive.

All other features and properties of these models are under analysis and will be presented and discussed in detail as soon as possibile.

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Discussion

Hirshi: Which rates are you using for the ^{17}O$(\alpha,\gamma)^{21}$Ne and the ^{17}O$(\alpha,n)^{20}$Ne nuclear reactions?

Chieffi: Caughlan & Fowler (1988) for the ^{17}O$(\alpha,\gamma)^{21}$Ne and the NACRE compilation (Angulo *et al.* 1999) for the ^{17}O$(\alpha,n)^{20}$Ne

Charbonnel: ^{14}N is a strong poison that captures neutron. Can you comment on its impact on the ^{13}C pocket you produce in the rotating models?

Chieffi: ^{14}N plays a fundamental role in the synthesis of Fluorine because it efficiently turns the neutrons produced by the ^{13}C$(\alpha,n)^{16}$O nuclear reaction in protons necessary to activate the ^{18}O$(p,\alpha)^{15}$N

Maeder: Could you please comment on the role of the ^{22}Ne pocket as a neutron source in your models?

Chieffi: We added this discussion in the text.

Alessandro Chieffi

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Physics of rotation: problems and challenges

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Abstract. We examine some debated points in current discussions about rotating stars: the shape, the gravity darkening, the critical velocities, the mass loss rates, the hydrodynamical instabilities, the internal mixing and N–enrichments. The study of rotational mixing requires high quality data and careful analysis. From recent studies where such conditions are fulfilled, rotational mixing is well confirmed. Magnetic coupling with stellar winds may produce an apparent contradiction, i.e. stars with a low rotation and a high N–enrichment. We point out that it rather confirms the large role of shears in differentially rotating stars for the transport processes. New models of interacting binaries also show how shears and mixing may be enhanced in close binaries which are either spun up or down by tidal interactions.

Keywords. Stellar Physics, Stellar rotation, Stellar evolution

1. Introduction

Interferometry, asteroseismology and spectropolarimetry have brought new evidences about the high impact of stellar rotation on the stellar structure and evolution. We can say that rotation influences all observational properties as it has an impact on all model outputs, whether for single or binary stars. The question is whether models and observations are in agreement. We concentrate in this review on current problems and new challenging questions regarding the effects of axial rotation on stellar structure and evolution. For basic developments on the effects of rotation on stellar structure, evolution and nucleosynthesis, the reader may see for example Maeder & Meynet (2012).

2. Shape, gravity darkening, critical velocities and mass loss

2.1. *Shape of rotating stars*

The classical Roche model assumes that the gravitational potential is only due to a central mass concentration. At critical rotation, i.e. when the outwards centrifugal force just compensates central gravity, the Roche model leads to an extreme ratio of the equatorial radius to the polar radius $R_{\rm e}/R_{\rm p} = 1.5$. (Structure models predict that the polar radius generally decreases by a few percents for extreme rotation, but this does not affect the critical ratio $R_{\rm e}/R_{\rm p}$).

The VLTI observations of fast rotating stars have led to many discussions, particularly in the case of the Be star Achernar. Domiciano de Souza *et al.* (2003) first found a value of 1.56 for the ratio of the equatorial to the polar radius of Achernar, which was a problem for the Roche model. Kervella & Domiciano de Souza (2006) have studied the oblateness of Achernar and shown that the observations are influenced by the presence of a circumstellar envelope along the polar axis, in addition to the rotational flattening of the photosphere. Carciofi *et al.* (2008) pointed out that the controversial observations may be better interpreted with the account of gravity darkening with in addition a small equatorial disk making the transition between the photosphere and the circumstellar

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environment. Delaa *et al.* (2013) also demonstrated in the case of α Cep the importance of a good determination of the position angle of the rotation axis, in addition to the other mentioned effects.

On the theoretical side, Zahn *et al.* (2010) went a step beyond the Roche model by accounting for the quadrupolar moment of the mass distribution for a star of $7\,M_\odot$ corresponding to Achernar. They showed that at critical velocity, the ratio $R_\mathrm{e}/R_\mathrm{p}$ exceeds the standard value of 1.50. In the case of uniform rotation, they found that the extreme ratios $R_\mathrm{e}/R_\mathrm{p}$ ranges from 1.526 to 1.516 as the star evolves on the Main Sequence (MS). In the case of shellular rotation (with angular velocity Ω constant on level surface and increasing with depth), the values range from 1.560 to 1.535 over the MS phase. Thus, accurate interferometric observations of stars at critical rotation might potentially provide internal constraints on their internal rotation.

2.2. *Gravity darkening*

The von Zeipel theorem (von Zeipel 1924) states that the flux $\vec{F}(\Omega,\vartheta)$ at given angular velocity Ω and colatitude ϑ on a uniformly rotating varies like the effective gravity $\vec{g}_\mathrm{eff}(\Omega,\vartheta)$, which is the sum of the Newtonian gravity and of the centrifugal acceleration. The von Zeipel theorem in the case of shellular rotation leads to (Maeder 1999),

$$\vec{F}(\Omega,\vartheta) = -\frac{L}{4\,\pi\,G\,M^\star}\,\vec{g}_\mathrm{eff}(\Omega,\vartheta)[1+\zeta(\Omega,\vartheta)] \quad \text{with} \quad M^\star = M\left(1-\frac{\Omega^2}{2\,\pi\,G\,\overline{\varrho}_M}\right). \tag{2.1}$$

L is the luminosity and $\overline{\varrho}_M$ the average density over the mass M. The reduced mass $M^\star$ was generally forgotten in previous studies, despite the fact that it should also be there in case of uniform rotation. The term $\zeta(\Omega,\vartheta)$ is only present in differentially rotating stars, it brings correcting terms depending on the Ω–gradient, the opacities and the gradient of μ (which also depends on ionization). Without the term ζ and the mass reduction, Eq. (2.1) implies that T_eff behaves likes g_eff^β, with $\beta = 0.25$ in the classical case. Claret (2012) has also found significant deviations from the classical case, which depend on the optical depth, on T_eff and on the adopted atmosphere model.

Several authors have attempted to determine the parameter β from interferometric observations, for recent references see Zhao *et al.* (2009); Che *et al.* (2011); Delaa *et al.* (2013). Che *et al.* support a value $\beta = 0.19$ for stars with $T_\mathrm{eff} > 7500$ K. Below, convective envelopes tend to appear and imply low β-value as shown long ago by Lucy (1967).

We emphasize that gravity darkening affects all photometric and spectroscopic observations. A rotating star may be seen as a composite star made of thousands local atmosphere models with different local values of g_eff and T_eff. Gravity darkening says how these parameters are distributed over the stellar surface. In addition, all these local models are seen with different limb–darkening effects.

2.3. *Critical velocities*

The classical expression of the critical or break–up velocity of a rotating star is

$$v_\mathrm{crit,1} = \left(\frac{GM}{R_\mathrm{e,crit}}\right)^{\frac{1}{2}} = \left(\frac{2}{3}\frac{GM}{R_\mathrm{p,crit}}\right)^{\frac{1}{2}}. \tag{2.2}$$

In massive stars, the high radiation pressure may add its outwards force to the centrifugal force and modify the expression of the critical velocity. One often finds in literature the following expression with the Eddington factor Γ,

$$v_\mathrm{crit} = \sqrt{\left(\frac{GM}{R_\mathrm{e,crit}}\right)(1-\Gamma)}\,, \tag{2.3}$$

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