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The influence of mass loss and rotation on the stellar yields from massive stars

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We briefly review the dependence of the yields provided by a generation of solar metallicity massive stars on the mass loss rate adopted in the WNE phase and beyond. We also show some very preliminary results concerning the evolution of a rotating 25 $M_{\odot}$ of solar metallicity computed by adopting an initial equatorial surface velocity of 300 km/s.

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1. Introduction

Electric forces constitute the main obstacle to the synthesis of the elements. High relative velocities among the particles, which imply high temperatures, high densities and long timescales are therefore required to activated the fusion of even the lightest particles. For this reason the basic environment in which appreciable nuclear fusions may occur is the interior of a star. Since the physical properties inside a star are basically controlled by its mass, the nucleosynthetic yields reflect its initial mass. Stars more massive than a threshold value (which is of the order of 10 $M_{\odot}$ for solar metallicity) never enter the electron degeneracy regime (or just very late in the evolution) and are therefore able to raise the temperature in the central region up to several billion degrees and hence synthesize via direct charged particle reactions nuclei up to those having the largest binding energy per nucleon, i.e. the iron peak nuclei. Stars less massive that this threshold value, viceversa, form a highly electron degenerate core whose role is, on one side, that of preventing the strong contraction required to reach very high temperatures, but, on the other side, it allows the activation of the so called thermally pulsing phase, which means the possibility of producing a variety of neutron fluxes and hence the nucleosynthesis of nuclei beyond the iron peak via multiple successive captures of these neutral particles up to the most massive stable ones. In the following we will concentrate on the basic evolutionary properties of massive stars and their yields.

In general, the yield of a given nuclear species is the result of a complex interplay among production rate, destruction rate, possible dilution over a mass region (as a consequence of convective motions) and eventually its ejection in the interstellar medium. The very steep dependence of the nuclear cross sections on the temperature, in fact, basically would concentrate the synthesis of any nucleus in a very narrow mass range; it is the presence of large convective motions that in many cases spreads the fresh results of the nucleosynthesis over a quite large mass interval where it may be preserved from further reprocessing and accumulated. The role of convective mixing is however multifold: in fact it also acts as a miner in the sense that it carries freshly synthesized material from the deep interior up to the surface where it can be ejected through the stellar wind and therefore preserved by further reprocessing. Convective motions may also bring inward fresh "fuel", with the consequent enhancement of the overall nuclear processing. Also mass loss plays a fundamental role in the determination of the final yields either because it directly controls the amount of mass ejected without further reprocessing, but also indirectly because it controls the mass of the star i.e. the leading parameter that drives its evolutionary properties: basically timescales, efficiency of the convective mixing, temperature and density.

Significant uncertainties in the evolutionary properties of the stars (including the explosion mechanism) as well as in the adopted basic input physics may reflect, even dramatically, on the final yields. Figs. 1 and 2 show, as an example, the final yields provided by a generation of massive stars as a function of the initial mass (for solar metallicity). The blue symbols refer to models computed by adopting the mass loss rate in the Early Wolf Rayet phase (WNE) and beyond proposed by [1] (hereinafter NL00) while the red symbols refer to models computed by adopting the prescription suggested by [2] (hereinafter LA89) for the same evolutionary phases. These yields refer to the models already presented by [3] and computed by imposing an explosion energy such that the final kinetic energy of the ejecta were 10^{51} erg for all masses. Note that since the LA89 mass loss rate is higher than the NL00 one, the former set of models reaches the core bounce with

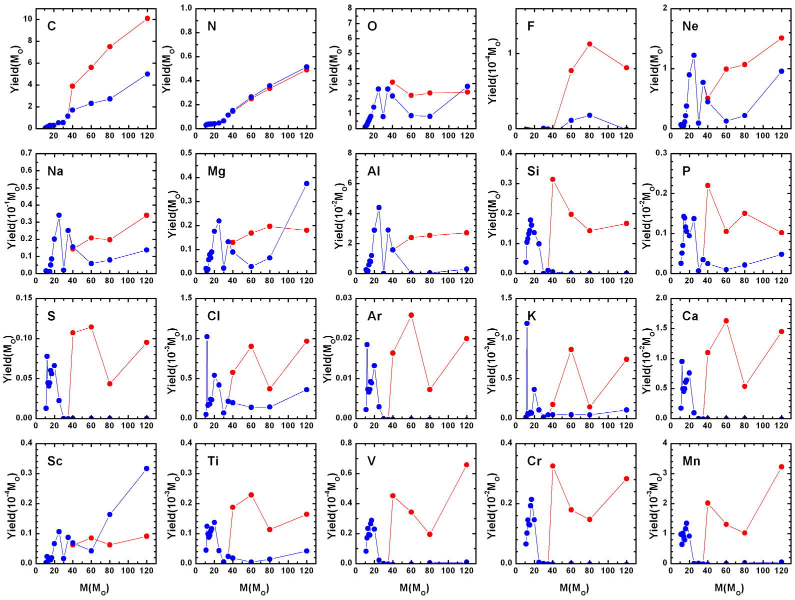

Figure 1: Yields in solar masses as a function of the initial mass. The blue dots connected by a blue solid line refer to models computed by adopting the NL00 mass loss rate in the WNE phase and beyond while the red dots connected by a red solid line refer to models computed by adopting the LA89 mass loss rate in the same evolutionary phases

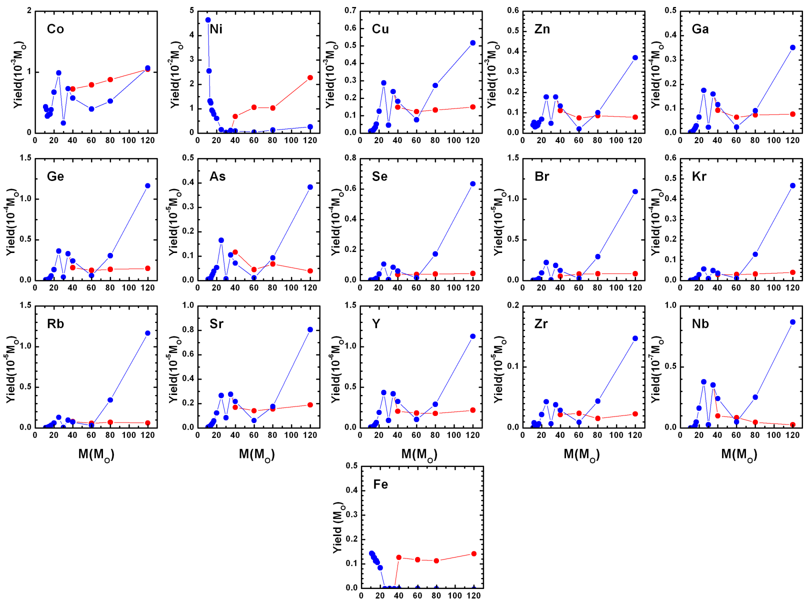

Figure 2: Fig.1 continued

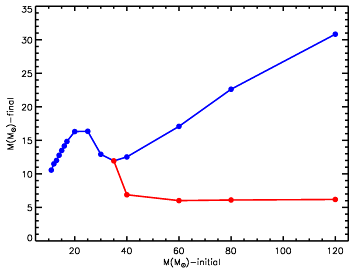

Figure 3: Initial-final mass relation. The blue dots connected by a blue solid line refer to models computed by adopting the NL00 mass loss rate in the WNE phase and beyond while the red dots connected by a red solid line refer to models computed by adopting the LA89 mass loss rate in the same evolutionary phases

smaller masses than the latter one. Fig. 3 shows the initial-final mass relation that is obtained in the two cases. Note that the minimum mass that becomes a WNE star (at least in this specific set of models) is the 35 $M_\odot$, so only models above this threshold value are affected by these different mass loss rates.

It is evident how the yields dramatically depend on the adopted mass loss rate in the WNE phase. Stars computed with the NL00 rate, preserve a much larger C-convective shell and hence the nuclei synthesized in this environment, like Sc, Cu, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr and Nb are produced in larger abundances than in the other case where the extension of the C-convective shell is strongly inhibited by the much smaller final mass of the star. Viceversa the models that end with the smaller final mass may eject more effectively all the nuclei preferentially produced by the explosive burnings (like Si, P, S, Cl, Ar, K, Ca, Ti, V, Cr, Mn, Fe and Ni). The reason is that the smaller the final mass the smaller the binding energy and hence the easier the ejection of matter located very deeply in the star.

Quite recently we began working on the influence of rotation on the evolution of stars and in particular on the yields. In the next section we will present some preliminary results concerning the presupernova evolution of a rotating 25 $M_\odot$ star.

2. Evolution of a 25 $M_\odot$ of solar metallicity with rotation

According to [4, 5] the structural deformations induced by rotation on a star may be mimicked, in a one dimensional code, by means of two "form factors", f_P and f_T, whose explicit formulation is given by:

$$f_P = \frac{4\pi r^4}{GMS_\Psi < g_{eff}^{-1} >}$$

$$f_T = \frac{16\pi^2 r^4}{S_\Psi^2 < g_{eff}^{-1} >< g_{eff} >}$$

where Ψ represents an equipotential surface, S_Ψ its area, $< g_{eff} >$ and $< g_{eff}^{-1} >$ the average gravity on the equipotential and the average of its inverse, respectively. Both these form factors tend to one as the angular velocity tends to zero and tend to zero as the angular velocity tends to the

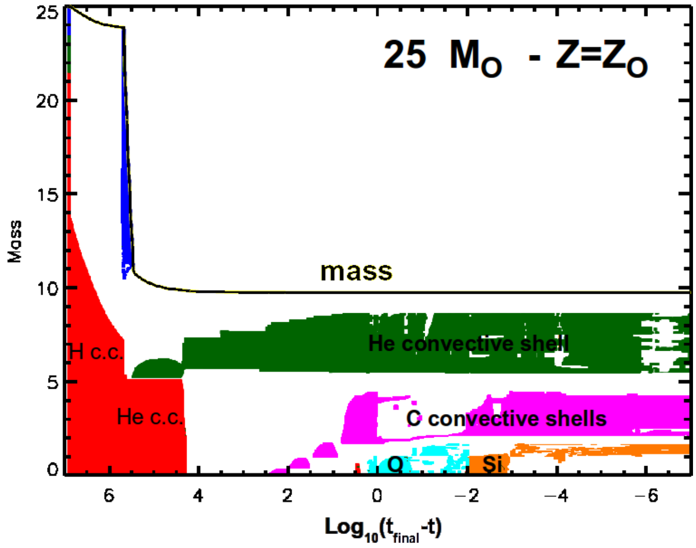

Figure 4: Extension of the various convective regions that form in a non rotating 25 $M_\odot$ during all its evolution from the central H burning phase up to the onset of the core collapse

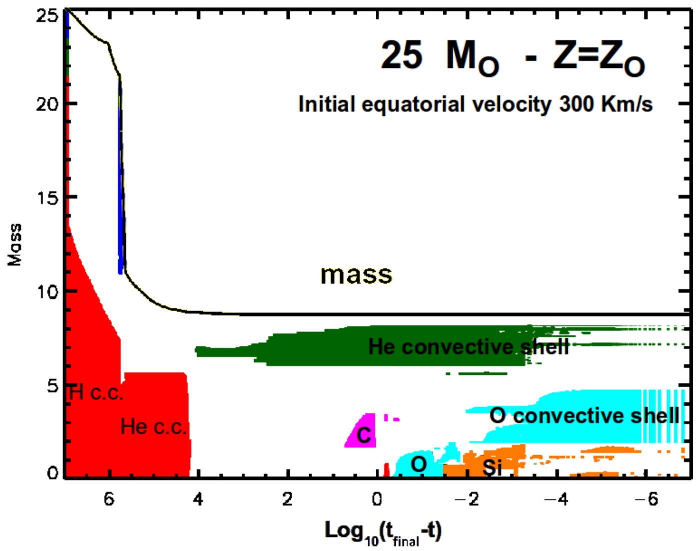

Figure 5: Extension of the various convective regions that form in a rotating 25 $M_\odot$ during all its evolution from the central H burning phase up to the onset of the core collapse

break out velocity. The two basic equations describing the hydrostatic equilibrium and the energy flux become, in this approximation:

$$\frac{dP}{dM} = -\frac{GM}{4\pi r^4} \times f_P$$

$$\frac{dlnT}{dlnP} = \frac{3\kappa LP}{16\pi acGT^4M} \times \frac{f_T}{f_P}$$

The form factor f_P in practice weakens the gravity force so that a smaller pressure gradient is necessary to sustain a rapidly rotating star. Only the ratio between f_T and f_P enters in the equation describing the energy flux and this ratio slightly increases above one as the rotational velocity increases. This means that in a rotating star the radiative temperature gradient is (slightly) steeper than in the non rotating case. In addition to these structural deformations, rotation triggers thermal and dynamical instabilities that lead to a redistribution of both the angular momentum and the chemical composition. In the present computations the redistribution of the angular momentum follows the advective-diffusive equation derived by [6, 7]:

$$\rho \frac{d}{dt}(r^2\omega)_{M_r} = \frac{1}{5}\frac{1}{r^2}\frac{\partial}{\partial r}(\rho r^4 \omega U) + \frac{1}{r^2}\frac{\partial}{\partial r}(\rho r^4 D_{shear}\frac{\partial \omega}{\partial r})$$

where U represents the velocity of the matter due to the meridional circulation [9, 10] - treated in this case as an advective process - while D_{shear} is the diffusion coefficient related to the shear process. All other quantities have their usual meaning. Following [8] we have adopted the following expression for the diffusion coefficient:

$$D_{shear} = \frac{8}{5}\frac{R_{ic}(rd\omega dr)^2}{N_T^2/(K+D_h)+N_\mu^2/D_h}$$

where

$$N_T^2 = \frac{g\delta}{H_P}(\nabla_{ad}-\nabla)$$

$$N_\mu^2 = \frac{g\delta}{H_P}(\frac{\varphi}{\delta}\nabla_\mu)$$

$$K = \frac{16\sigma T^3}{3c_p\kappa\rho^2}$$

δ $(\equiv -dln\rho/dlnT)_{\mu,P}$ and ϕ $(\equiv dln\rho/dln\mu)_{P,T}$ are two well known thermodynamical derivatives, H_P $(\equiv P/\rho g)$ the pressure scale height, K the thermal diffusion coefficient, D_h $(\sim rU)$ the horizontal diffusion coefficient [9] and R_{ic} $(=0.25)$ the critical Richardson number.

As for the mixing of the chemical composition, vice versa, also the meridional circulation may be described by a pure diffusive process [6] so that in this case a pure diffusion equation may be used and the total diffusion coefficient becomes:

$$D = D_{shear} + D_{mer.circ.} = D_{shear} + \frac{rU}{30}$$

A full discussion of the evolutionary properties of our new set of rotating models will be presented shortly together to the latest version of the FRANEC code. Here we simply show some preliminary results concerning the final presupernova structure of a 25 $M_\odot$ star of solar metallicity, computed by adopting an initial solid body rotation with a surface equatorial velocity of 300 Km/s. As a reference, Fig. 4 shows the Kippenhahn diagram computed without rotation, while the similar diagram obtained for the rotating model is shown in Fig. 5. The first thing worth noting is that the

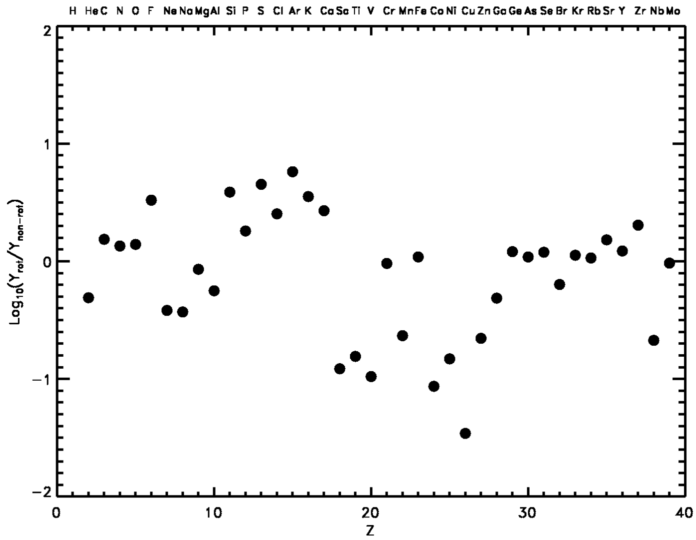

Figure 6: ratio between the preexplosive yields obtained for the rotating and the non rotating 25 $M_{\odot}$ star

total mass of the star at central He exhaustion is smaller for the rotating model; the reason is that this model lives longer and hence mass loss has more time to erode the surface of the star. As a consequence of this smaller final total mass the He convective shell is significantly smaller. The most striking feature is however the merging of the O and the C convective shells while the star is in central Si burning. The merging of these two shells shuffles and homogenizes the chemical composition and it is not clear which will be the effect on the final yields of the nuclei produced by the Ne and C explosive burnings. Fig. 6 temptatively shows the *preexplosive* ratio between the yields of the rotating to the non-rotating stellar model. The region of the intermediate mass nuclei (Si to Zn) should not be looked at because all these elements will be fully reprocessed by the explosive burnings. Viceversa the points referring to the light elements (specifically He to Al) could be meaningful. He appears significantly underproduced (by a factor of two or so), while the CNO group is slightly overproduced though it preserves the relative abundances that are obtained in the non rotating case. F viceversa results significantly overproduced (by a factor of four or so) while Ne and Na show a reduction by a similar amount. Mg is basically unaffected while Al is mildly reduced (by a factor of two or so). Also the yields obtained for the weak *s* process component (Ga to Mo) should be quite meaningful because they nuclei are produced in regions where no explosive nucleosynthesis occurs: it seems that the bulk of these nuclear species are not largely affected by the rotation. Of course a more detailed analysis covering a full massive star spectrum should be studied before driving any "firm" conclusion on the impact of rotation on the chemical evolution history of our galaxy.

3. Conclusions and acknowledgements

We have shown how dramatic is the dependence of the yields on the adopted mass loss rate in the WNE phase and beyond. We have also briefly reported a preliminary evolution of a rotating 25 $M_{\odot}$. A full set of rotating massive stars computed from the Pre Main Sequence phase to the core

collapse plus the following explosive nucleosynthesis will be published shortly. We acknowledge the ASI-INAF contract I/016/07/0 and the PRIN-INAF 2009 for financial support.

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