

Rotating massive stars: Pre-SN models and stellar yields at solar metallicity

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We present a new set of stellar yields obtained from rotating stellar models at solar metallicity covering the massive star range (9–120 M_{\odot}). The stellar models were calculated with the latest version of the Geneva stellar evolution code described in [1]. Evolution and nucleosynthesis are in general followed up to Silicon burning. The contributions from stellar winds and from supernova explosions to the stellar yields were calculated separately. The two contributions were then added to compute the total stellar yields [2].

The effects of rotation on pre-supernova models are significant between 15 and 30 M_{\odot} . Above 20 M_{\odot} , rotation may change the radius or colour of the supernova progenitors (blue instead of red supergiant) and the supernova type (IIb or Ib instead of II). Rotation increases the α and CO core sizes by a factor ~ 1.5 . **Thus, rotation increases the yields for heavy elements and in particular for carbon and oxygen by a factor 1.5–2.5.** Rotating models produce larger yields for ^{12}C and ^{16}O in the mass range between 9 and about 35 M_{\odot} compared to the 1992 calculations [3].

For Wolf-Rayet stars ($M \gtrsim 30M_{\odot}$), the pre-supernova structures are mostly affected by the intensities of the stellar winds and less by rotation [4]. In this mass range, rotation increases the yields of helium and other hydrogen burning products but does not significantly affect the yields of elements produced in more advanced evolutionary stages. Note that the final masses of the most massive stellar models ($\sim 120 M_{\odot}$) are similar to the final masses of less massive stars ($\sim 40 M_{\odot}$) due to the use of revised mass loss rates from Nugis and Lamers 2000 [5]. The most massive stars are therefore also expected to form black holes.

1. Introduction

Over the last ten years, the development of the Geneva stellar evolution code has allowed the study of the evolution of rotating stars until carbon burning. The models can reproduce many observational features at various metallicities, like surface enrichments [9], ratios between red and blue supergiants [10] and the population of Wolf-Rayet (WR hereinafter) stars [4]. In [1], we describe the recent modifications made to the Geneva code and the evolution of our rotating models until silicon burning. In this contribution, we briefly present the stellar yields for rotating stars at solar metallicity with a large initial mass range (9–120 M_{\odot}).

2. Computer model

The computer model used to calculate the stellar models is described in detail in [1]. Convective stability is determined by the Schwarzschild criterion. Convection is treated as a diffusive process from oxygen burning onwards. The overshooting parameter is $0.1 H_P$ for H and He–burning cores and 0 otherwise. On top of the meridional circulation and secular shear, an additional instability induced by rotation, dynamical shear, was introduced in the model. The reaction rates are taken from the NACRE [11] compilation for the experimental rates and from the NACRE website (<http://pntpm.ulb.ac.be/nacre.htm>) for the theoretical ones. The mass loss rates used are described in [4]. In particular, during the Wolf–Rayet phase, we use the mass loss rates by Nugis and Lamers 2000 [5]. These mass loss rates, which account for clumping effects in the winds, are smaller by a factor 2–3 than the mass loss rates used in our previous non–rotating, “enhanced mass loss rate” stellar grids [12].

We calculated stellar models with initial masses of 9, 12, 15, 20, 25, 40, 60, 85 and 120 M_\odot at solar metallicity, with initial rotation velocities of 0 and 300 km s^{-1} . The value of 300 km s^{-1} corresponds to an average velocity of about 220 km s^{-1} on the Main Sequence (MS) which is very close to the observed average value [13]. The calculations start at the ZAMS. The rotating 15, 20, 25, 40 and 60 M_\odot models were computed until the end of core silicon (Si) burning. Their non–rotating counterparts were computed until the end of shell Si–burning. For the rotating 12 M_\odot star, the model ends after oxygen (O) burning. For the non–rotating 12 M_\odot star, neon (Ne) burning starts at a fraction of a solar mass away from the centre but does not reach the centre and the calculations stop there. The evolution of the models with initial masses between 12 and 60 M_\odot is described in [1]. The 9, 85 and 120 M_\odot models are presented in [4] and their evolution was followed until the end of the core He–burning (the SN yields calculation for these last models is described in [2] and follows the method used in [3]).

3. Results

3.1. Contributions to yields from stellar winds and SN explosions

Before we discuss the stellar yields, it is useful to recall the influence of rotation on the final mass of the different models (presented in [4, 2]). Below $30 M_\odot$, rotating models lose significantly more mass than non–rotating models [14]. For WR stars ($M \gtrsim 30 M_\odot$), the new mass loss prescription [5], including the effects of clumping in the winds, results in mass loss rates that are a factor of two to three smaller than the rates from [15]. As a result, the final mass of WR stars in the present calculation are noticeably larger than in 1992 [3]. There is no clear difference between the final mass of rotating and non–rotating models. For a model with an initial mass larger than $30 M_\odot$, the final mass is always between 11 and $17 M_\odot$. Black hole formation is therefore expected for all the very massive stars at solar metallicity.

What is the relative importance of the wind and SN contributions? Figure 1 displays the total stellar yields divided by the initial mass of the star as a function of its initial mass, m , for the non–rotating (left) and rotating (right) models. The different total yields (divided by m) are piled up. ^4He yields are delimited by the top solid and long dashed lines (top shaded area), ^{12}C yields by the long dashed and short–long dashed lines, ^{16}O

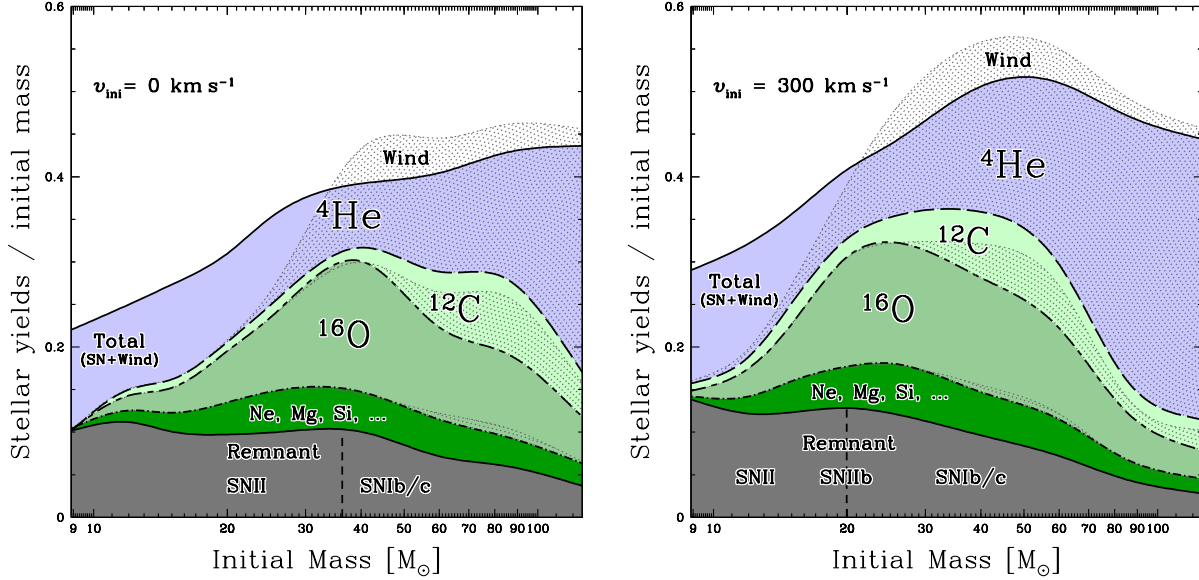


Figure 1. Stellar yields divided by the initial mass as a function of the initial mass for the non-rotating (left) and rotating (right) models at solar metallicity.

yields by the short-long dashed and dotted-dashed lines and the rest of metals by the dotted-dashed and bottom solid lines. The bottom solid line also represents the fraction of the star locked in the remnant (M_{rem}/m). The corresponding SN explosion type is also given. The wind contributions are superimposed on the total yields for the same elements between their bottom limit and the dotted line above it. Dotted areas help quantify the fraction of the yields due to winds. Note that for ${}^4\text{He}$, the total yields are smaller than the wind yields due to negative SN yields for ${}^4\text{He}$.

For ${}^4\text{He}$ (and other H-burning products like ${}^{14}\text{N}$), the wind contribution increases with mass and dominates for $M \gtrsim 22M_{\odot}$ for rotating stars and for $M \gtrsim 35M_{\odot}$ for non-rotating stars. These mass limits correspond to the lower mass limits for WR star formation. For very massive stars, the SN contribution for ${}^4\text{He}$ is negative (this is possible because, in the yield calculation, the initial composition is deducted from the final one) and this is why the wind contribution is higher than the total one. For ${}^{12}\text{C}$, the wind contributions only start to be significant above the mass limits for WR star formation (22 and $35 M_{\odot}$ for rotating and non-rotating models respectively). This is expected because a star must have ejected most of its helium before it can eject carbon. Above these mass limits, the contribution from the wind and the SN are of similar importance. For ${}^{16}\text{O}$, the wind contribution remains very small because with the new mass loss prescription, the oxygen rich layers are not uncovered.

3.2. Total stellar yields

Our non-rotating models were compared to the literature [6, 7, 8] and are consistent with other calculations. Differences can be understood in the light of the treatment of

convection and the rate used for $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ [2]. This verifies the accuracy of our calculations and gives a safe basis for studying the effects of rotation on the yields.

For H–burning products, the yields of the rotating models are usually higher than those of non–rotating models. This is due to larger cores and larger mass loss. However, between about 15 and 25 M_{\odot} , the rotating yields are lower. This is due to the fact that the winds do not expel much H–burning products yet, and more of these products are burned later in the pre–supernova evolution (giving negative SN yields). For very massive stars ($M \gtrsim 60 M_{\odot}$), rotating stars enter into the WR regime in the course of the MS. In particular, the long time spent in the WNL phase (WN star showing hydrogen at its surface [4]) results in the ejection of large amounts of H–burning products. Rotation therefore increases the H–burning product yields in this mass range.

Concerning He–burning products, below 40 M_{\odot} , most of the ^{12}C comes from the SN contribution. In this mass range, rotating models, having larger cores, also have larger yields (factor 1.5–2.5). For very massive stars ($M \gtrsim 60 M_{\odot}$), the situation is reversed for He–burning products because of the different mass loss history. As said above, rotating stars enter into the WR regime in the course of the MS. The long time spent in the WNL phase [4] results in a large mass loss. Therefore, very massive rotating stars have a small total mass early in their evolution and end up with smaller cores. Compared to 1992 [3], the ^{12}C yields are larger in the present rotating models for masses lower than 30 M_{\odot} and smaller for masses higher than 30 M_{\odot} . Since very massive stars are much less numerous, we expect the overall ^{12}C yield of rotating models to be larger than those of 1992 [3]. The situation for ^{16}O and the total metallic yields is similar to carbon. Therefore ^{16}O and metallic yields are usually larger for our rotating models than for our non–rotating ones by a factor 1.5–2.5.

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