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Nucleosynthesis in rotating massive stars

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Observational evidence for rotationally induced mixing in massive stars is summarized. From these observations and the models required to explain them, we conclude that rotation will increase the primary metal yields of massive stars, enhance the production of H-burning secondary products (e.g. ^{14}N and ^{26}Al), and reduce the initial stellar mass limit for Type II supernova explosions. For the first time, these features are described quantitatively in the context of new evolutionary models for mass losing, rotating stars. These calculations include the effects of the centrifugal force on the structure as well as angular momentum transport and chemical element diffusion. The chemical yields of these models are presented and compared to those of other models evolved without rotation. Our models also indicate the presence of qualitatively new nucleosynthesis channels which may result in primary ^{14}N production in the H-burning shell and primary neutron processing in the He-burning shell of rotating stars. Implications for the supernova explosion and neutron star remnant are briefly described.

1. INTRODUCTION

Massive stars ($M_{\rm initial} \gtrsim 8\,M_\odot$) constitute the most important nucleosynthesis site in the universe. They produce, in our Galaxy and others, most of the elements between oxygen and calcium [1,2], perhaps as much as 1/2 of the iron [3], most of the s-process up to about A = 90, and, very likely the r-process nuclei [6]. Metallicity dependent stellar evolution models incorporating detailed nucleosynthesis networks [1,7] and subsequent chemical evolution calculations [8] find good quantitative agreement with the solar system abundances, especially the elements O - Ca (cf. also Woosley, this volume). In view of these successes, one may be tempted to assume that models for massive star evolution are free of major problems. However, despite the generally good agreement with observations, some unresolved issues still indicate that much remains to be done:

1. *Which stars are the main producers of* ^{12}C? While it is generally assumed that intermediate mass stars dominate [9], it was recently shown [10] that metallicity dependent mass loss leads in the course of Galactic chemical evolution to a delayed carbon production from massive stars which appears to have the correct time dependence and to yield roughly the amount of carbon found in the Galaxy today (cf. also Prantzos, this volume). Calculations without mass loss on the other hand only make about 1/3 the solar carbon abundance [1,8].

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2. *Do massive stars produce primary ^{14}N?* The primary nature of ^{14}N is indicated by the constancy of the [N/Fe] abundances with metallicity in Galactic dwarf stars [11,12]. While most of the galactic nitrogen may come from intermediate mass stars [8,9], strong nitrogen enrichment in very metal poor stars ([Fe/H]$\lesssim -2$) [11,12], in globular cluster stars [13,14], and in the ISM of star forming low metallicity galaxies [15] suggests a massive star origin for nitrogen in these objects. So far no robust method of primary nitrogen production in massive stars has been published (though see [8]).

3. *What is the main source of ^{26}Al in the Galaxy?* The patchy structure in the map of the Galactic 1.8 MeV emission (cf. Diehl, this volume) indicates a very young age of the source of this radionuclide and thus a massive star origin. While the ^{26}Al contribution from H-burning massive stars [16] appears to be insufficient in standard models [17], a Type II supernova origin of ^{26}Al is possible if the Schwarzschild criterion for convection is correct [1,18,19]. This predicts a mass of ^{60}Fe that should soon be detectable and may pose a problem if it is not ([20]; Leising, this volume).

4. *Where is the main site of the r-process?* While there may be more than one way of making the r-isotopes [21], extremely metal poor halo stars already show the solar system r-process pattern for nuclei with A$\gtrsim$ 140 [22,23]. The high [r/Fe] ratio, the large spread in [r/Fe] at the lowest metallicities ([Fe/H]$\lesssim -2.5$) [23], and the large C/O ratio in at least one [22] and possibly more (Beers & Cowan, private comm.) r-process enriched metal poor stars are consistent with r-process nucleosynthesis in the explosive He-shell burning of $\sim 10\,M_\odot$ stars [24], among other possibilities.

These issues, and others, may be connected with persistent uncertainties in massive star modeling, especially mass loss, convection and rotation. While the first two subjects, mass loss and convection, have been extensively investigated during the last two decades [25,26], effects of rotation have been largely ignored. The remainder of this paper will show that rotation is in fact important, and relevant to all four questions posed above.

2. OBSERVATIONS

Massive stars are rapid rotators. Equatorial rotation velocities span the range $v_{\rm rot} = 100 - 400\,{\rm km\,s^{-1}}$, with B stars rotating closest to their break-up speed $v_{\rm crit}$, and values of $v_{\rm rot}/v_{\rm crit} = \omega_{\rm rot}/\omega_{\rm crit} = 0.5$ frequently observed for O stars [27]. During the last decade, many observations have revealed unusual surface abundances that may require additional internal mixing (beyond that of simple convection) for their explanation:

CNO: OBN stars have been found to be nitrogen enriched and carbon depleted [28]. It is suspected that even spectroscopically normal OB supergiants are nitrogen-rich, and that only the rare carbon-strong OBC stars show unaltered abundances [29]. The SN 1987A progenitor showed evidence of CNO processing [30]. A considerable fraction of main sequence B stars was found to be nitrogen enriched [31], and B [32] and A supergiants [33] were also found to be N-enriched, with abundances unlike those expected from dredge up as a red supergiant. In red giants, the ^{12}C/^{13}C-ratio was found to be smaller than expected just from convective dredge-up [34] and the WN/C stars show, simultaneously, the products of hydrogen and helium burning at their surface [35,36].

Helium: Helium is observed to be enriched in a large fraction of main sequence O stars [37] and in several main sequence B stars [31].

Sodium: Sodium — which is synthesized during hydrogen burning in the NeNa-cycle — has been found to be strongly enriched in several G and K supergiants [38].

Boron: A strong boron depletion has been found in all (five) main sequence B stars [39] analyzed so far, with B/N ratios that exclude the possibility of mass exchange in close binary systems as explanation.

Altogether, the occurrence of some form of additional mixing responsible for altering the surface abundances in a large fraction, if not all massive stars is beyond reasonable doubt. If this mixing is due to rotation, then the nucleosynthetic yields of a large number of isotopes are different in (more realistically) rotating stars than in non-rotating ones (cf. Section 3.2) .

3. NUCLEOSYNTHESIS IN ROTATING STARS: FIRST RESULTS

Here we report on results obtained with a 1D implicit hydrodynamic stellar evolution code [41], which was modified to incorporate several effects of rotation [42]. The angular momentum is treated as a local variable. The centrifugal force is included in an angle-averaged form, with non-spherical equipotential surfaces replacing the usual Lagrangian mass variable as independent spatial coordinate [43]. The approximate constancy of all physical variables on equipotential surfaces is due to the action of the baroclinic instability [44]. The transport of chemical elements and angular momentum is performed in the diffusion approximation, with diffusion coefficients appropriate for the following instabilities: convection, semiconvection, dynamic and secular shear instability, Goldreich-Schubert-Fricke instability and Eddington-Sweet circulation. Mass loss due to stellar winds is taken into account, which is important to maintain a significant angular momentum gradient and thus efficient rotational mixing [45].

Though the dependence of the mixing on local physical quantities is properly accounted for in the appropriate diffusion coefficients, several model parameters had to be empirically adjusted. This was done by **a)** computing $1\,M_{\odot}$ models and reproducing the solar light element surface abundances, convection zone depth, and the time evolution of the rotation rate and the lithium surface abundance of solar type stars [46], and **b)** reproducing the CNO and helium surface abundance distribution of OB main sequence stars [31]. Our parameterization is thus semi-empirical. Other perhaps more mathematically rigorous methods exist, but still fail so far in reproducing the observations mentioned in Section 2 [47].

We have identified three different major effects of rotation on the chemical yields of massive stars, which are discussed in the following subsections.

3.1. Core sizes

One expects that centrifugal acceleration would lead to a reduced effective gravity and thus to a reduction in the stellar luminosity and convective core mass. However, this effect is small compared to the result of continuous rotationally induced mixing of fuel into the convective core, which leads to a larger value of the average mean molecular weight compared to the non-rotating case, and thus to a larger luminosity and consequently to larger convective core masses. This effect is quantitatively illustrated in Figure 1 for the H-burning phase of stars in the initial mass range $5...20\,M_{\odot}$ which shows that core masses at this stage of evolution can be increased by up to a factor of 2. The effect persists

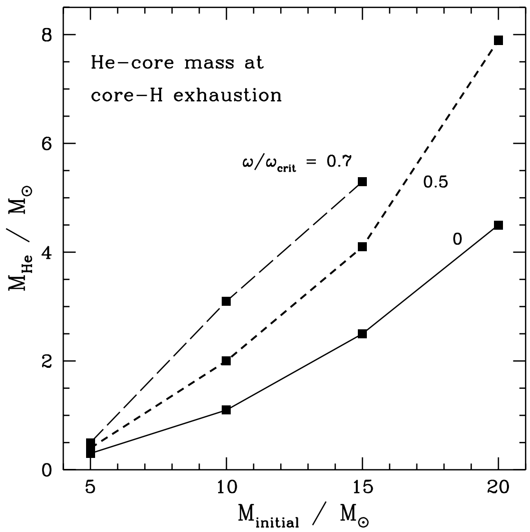

Figure 1. Mass of the He-core at core-H exhaustion for models with an initial mass of 5, 10, 15, and 20 $M_\odot$, for the non-rotating case (solid line), and for models which started core hydrogen burning with 50% (short dashed) and 70% (long dashed) of their critical rotation rate.

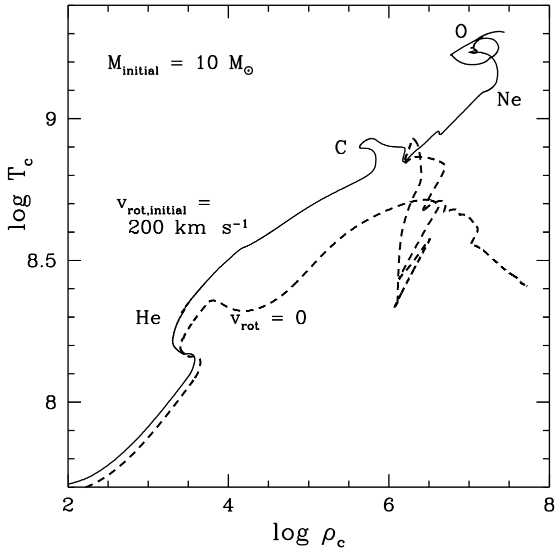

Figure 2. Evolutionary tracks of a rotating (solid line) and a non-rotating (dashed line) 10 $M_\odot$ star in the $\log \rho_c - \log T_c$–diagram. The various core burning stages are indicated along the track of the rotating model.

Table 1
Production factors (i.e. output vs. input) of some secondary isotopes, and ^{26}Al mass in the stellar ejecta at the time of the supernova explosion, for several rotating and non-rotating stars of solar metallicity. Note that for ^{23}Na and ^{26}Al, only the contribution due to hydrogen burning is considered.

$M/M_\odot$	v_{rot}/v_{crit}	f(^{13}C)	f(^{14}N)	f(^{17}O)	f(^{23}Na)	^{26}Al / $10^{-5}\,M_\odot$
8	0	2.9	3.9	20	1.8	0.01
8	.20	3.0	4.8	23	2.3	0.03
8	.40	2.9	6.0	35	2.8	0.11
20	0	3.0	4.0	18	2.9	0.84
20	.30	2.6	6.2	22	3.7	3.1
20	.40	2.7	7.2	21	4.2	3.8
20	.50	2.6	9.8	21	4.5	3.5

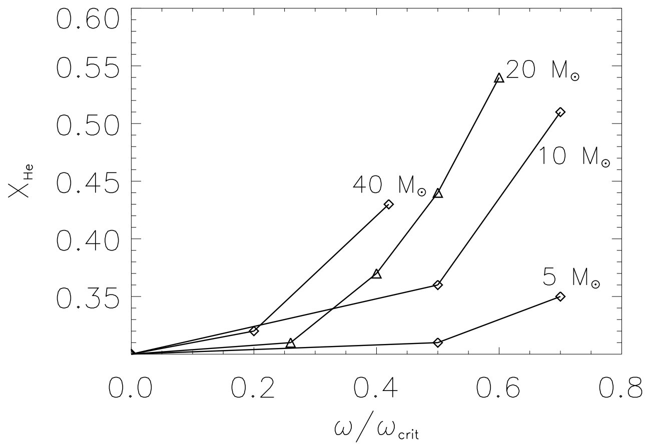

Figure 3. He surface mass fraction at core hydrogen exhaustion for models with an initial mass of 5, 10, 20, and 40 $M_{\odot}$, as function of the initial ratio of rotation to critical rotation velocity.

during later burning stages, e.g. helium cores of a given mass develop larger C/O-cores the faster they rotate. The chemical yields of primary isotopes (e.g. ^{12}C, ^{16}O, ... , ^{40}Ca) are increased according to the core mass increases. Further marked consequences are **a)** a different IMF-exponent due to the different stellar mass-luminosity relation, and **b)** a shift of the lower initial mass limit for core collapse and Type II supernova explosion to $\sim 5\,M_{\odot}$. The latter feature is demonstrated in Figure 2 by comparing the central evolution of a rotating and a non-rotating $10\,M_{\odot}$ star (cf. also Sect. 4).

3.2. Changes in envelope composition

As protons are mixed into the core during central H-burning, H-burning products are mixed into the whole radiative envelope. That this process is efficient enough to bring them even up to the stellar surface is demonstrated by many observations quoted in Section 2. Since the abundance of a H-burning product throughout the stellar envelope must be at least as large as its observed surface abundance, and since the envelope mass is usually larger than the core mass, this implies a large enhancement of H-burning products by rotation.

Figure 3 shows the surface helium abundance at the end of the main sequence evolution for solar metallicity stars of various masses and rotation rates. For stars with average rotation rates, a measurable helium surface enrichment is obtained only for $M_{\mathrm{initial}} \gtrsim 10\,M_{\odot}$, while rapidly rotating $20\,M_{\odot}$ stars may already during core hydrogen burning evolve into Wolf-Rayet stars [48]. Table 1 compares the production of several secondary H-burning products in rotating and non-rotating stars. We see that rotation can increase the yields e.g. of ^{14}N and ^{23}Na by a factor of a few. Furthermore, the ^{26}Al yield due to H-burning in 8...20 $M_{\odot}$ stars is increased by such large factors that it can no longer be neglected in comparison to the ^{26}Al yields due to supernovae or WR stars [17].

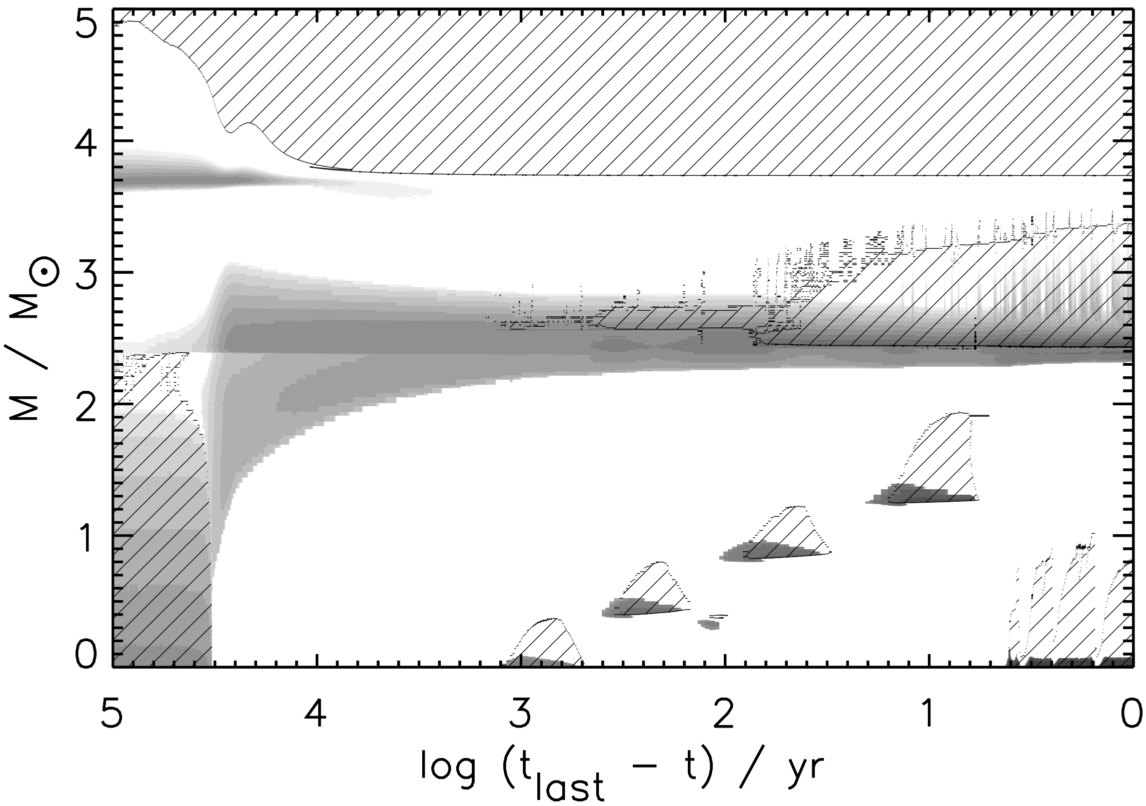

Figure 4. Structure of the inner $5\,M_\odot$ of a rotating star with an initial mass of $12\,M_\odot$, an initial equatorial rotation velocity of $200\,\mathrm{km\,s^{-1}}$ and solar metallicity, from core-He exhaustion through core-O burning. The abscissa is the logarithm of the time left until core collapse, and the ordinate is the mass enclosed in successive equipotential surfaces (cf. text). Dark shading indicates net positive nuclear energy generation, with the grey scale extending from $10^{-1}\,\mathrm{erg\,g^{-1}\,s^{-1}}$ (lightest grey) to $10^{12}\,\mathrm{erg\,g^{-1}\,s^{-1}}$ (darkest shading). Hatched regions are convectively unstable. The final stellar mass is $10.4\,M_\odot$, and the convective H-rich envelope extends down to $M \simeq 3.8\,M_\odot$. The He-burning shell is located at $M \simeq 2.5\,M_\odot$. During the last several 100 years the combined action of rotational mixing processes and the extending convective shell above the He-shell source episodically sweeps protons into the helium burning region, which leads to a flickering of the shell source and associated neutron production events.

3.3. Qualitatively new nucleosynthesis - primary N and the r-process

Just as rotation alters the composition of the H-rich envelope of massive main sequence stars, it can also mix the ashes of advanced burning stages with the radiative mantles above the burning cores, though this process is limited by the progressively shorter evolutionary time scales. Qualitatively new nucleosynthesis channels are opened in the situation where this mixing can transport the products of one burning phase to the site of a neighboring burning stage. This remains difficult however as neighboring burning stages are frequently separated by large entropy differences. However, we have identified two possibilities: **a)** When — during late burning stages — the H-burning shell becomes extinct, protons can be transported into the helium burning shell source (Figure 4). **b)** In stars of very low metallicity, the entropy difference between the H- and He-burning shell is small. In a $20\,M_\odot$ star of $Z = 10^{-3}Z_\odot$, we find ^{12}C to be injected into the H-burning shell and protons into the He-burning shell.

The injection of protons into helium burning results in a large rapid release of neutrons via $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{C}(\alpha,n)$. We are presently exploring the consequences but it is already clear that if a considerable amount of protons can be injected into the He-shells of stars of $\sim 10\,M_\odot$, this site may become again interesting as r-process source either before or during the supernova explosion [49]. In any case, the rather mild s-process usually associated with massive stars will change dramatically. Furthermore, a similar mechanism might act in thermally pulsating AGB stars where the periodic fading of the H-burning shell results in a periodic reduction of the entropy barrier between the H- and He-burning shell. I.e., rotational mixing is a candidate for producing the ^{13}C-pocket needed to operate the main component s-process in ABG stars (cf. Gallino, this volume).

The injection of ^{12}C into the H-burning shell on the other hand results in the production of primary ^{14}N. About $0.01\,M_\odot$ of ^{14}N are synthesized in this way in our rotating metal-poor ($10^{-3}\,Z_\odot$) $20\,M_\odot$ star. This may be sufficient to account for the nitrogen observed in the most metal poor stars (cf. Sect. 1). However, the investigation of the mass and metallicity dependence of this process needs further studies of rotating low-metallicity stars.

4. IMPLICATIONS FOR THE SUPERNOVA AND NEUTRON STAR

We have carried two versions of our 15 $M_\odot$ star to neon depletion. One model was evolved without rotation, both included mass loss. Details of these calculations will be presented elsewhere [50], however, several qualitative results of considerable interest for nucleosynthesis and high energy astrophysics are already apparent.

First, the large helium cores shown in Fig. 1 persist to the end. The non-rotating 15 $M_\odot$ model had a final helium core of 3.8 $M_\odot$; the rotating model had a core of 5.1 $M_\odot$. Because of the larger helium core, the rotating star died with a larger luminosity and experienced more mass loss. Thus its hydrogen envelope was reduced both from above and below (final total masses were 13.6 and 10.9 $M_\odot$ respectively without and with rotation). Because of the larger helium core, heavy element nucleosynthesis in this 15 $M_\odot$ star will resemble more closely that of the 18 $M_\odot$ star of ref. [1] which had a similar helium core mass. Such a recalibration of main sequence masses and helium core masses is expected across the board. Galactic chemical evolution calculations will need to be redone using these different calibrations. To first order, one expects that the good agreement with solar abundances found in [8] will persist, but that the star formation rate in the chemical evolution model will need to be reduced to accommodate the greater number of supernovae that results from the larger range of stellar masses contributing.

Because of the shift in helium core mass corresponding to a given ZAMS mass, the transition from stars that burn carbon convectively in their centers to those that burn radiatively will occur at a mass lower than 19 $M_{\odot}$, perhaps 16 $M_{\odot}$. But, using the same prescription, the lower limit for supernovae moves down to ~ 5 $M_{\odot}$. Since one is constrained by the observed supernova rate, the number and distribution of neutron star masses reported in [51] may not be greatly altered, but the fate of a given main sequence star will be.

Second, we estimate the amount of angular momentum that remains in the cores of these massive stars when they die to be in the range $j \simeq 10^{15}...10^{16}\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ in the inner 2 $M_{\odot}$, with a considerable error bar. These numbers exceed the angular momentum of even a rapidly rotating neutron star like the Crab by one to two orders of magnitude. However, the post-neon burning evolution of our models is still to be calculated, and the amount of angular momentum lost during and immediately following the supernova explosion is unknown. With considerable uncertainty, our calculations suggest that rotation may have a significant effect during the development of the explosion.

Third, since the amount of rotation remaining in the helium core is sensitive to mass loss, one expects two qualitatively different classes of pulsars to emerge from Type II and Ib supernovae respectively. Type Ib supernovae require that the star lose not only its hydrogen envelope, but an appreciable fraction of its helium core as well (e.g., [52]). The loss of mass from the surface leads to expansion and a slower rotation speed in the outer layers which is communicated to the inner core. By the time it explodes, the angular momentum in the iron core of a Type Ib supernova will have a much slower rotation rate than that in a star that did not lose part of the helium core. Since Type Ib supernovae probably occur preferentially in close binaries and many of them may remain bound after the explosion, a class of slowly rotating neutron stars in binary systems is predicted. This would be an interesting test of both the angular momentum transport calculation and current views regarding mass loss in massive Wolf-Rayet stars.

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