Nucleosynthesis in Rotating Stars

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Abstract. When stars rotate, internal mixing is induced which otherwise would not occur. Unlike convection, rotationally induced mixing can carry nuclear processed material into the cool, radiatively stable layers of a star and, at the same time, bring additional fuel from these layers into nuclear burning zones. Consequently both the final structure of the star and its chemical yields are altered. Unlike convection, rotationally induced mixing also has the potential to penetrate the entropy and composition barriers near burning shells. This can lead to new nucleosynthesis channels that would not exist in non-rotating stars. For example, we show here that rotation can mix protons into the helium shell and lead to the significant production of ^{15}N and ^{19}F. We also show that rotational mixing enhances the *s*-process and might even have consequences for the *r*-process.

1 Introduction

While the efficient mixing of composition in non-rotating stars happens only by convection and semiconvection, additional processes can occur in rotating stars (Pinsonneault 1997). For massive stars, the two most important are Eddington-Sweet circulation, with an efficiency that scales with $\Omega^2/\tau_{\rm KH}$ (Zahn 1992) – with $\tau_{\rm KH}$, the Kelvin-Helmholtz time scale and Ω the ratio of the rotation rate to the critical rotation rate – and the shear instability, which depends (chiefly) on the radial gradient of the angular velocity. It is not straightforward to derive the efficiency of these mixing processes, and, in particular, the inhibiting effect of a gradient in the mean molecular weight, μ, is poorly known. Recent approximations for these instabilities in the linear regime have been derived by Maeder & Zahn (1998), but their non-linear behavior remains largely unexplored.

In this paper, we focus mainly on stars sufficiently massive to become Type II supernovae. These stars are known to be born with rotation rates of order tens of percent of the critical value. Even if these stars rotated almost rigidly during core hydrogen burning, such large angular velocities would result in strong Eddington-Sweet circulation. Consequently these stars often show signs of nuclear processing at their surfaces (see below). Beyond core hydrogen exhaustion, all stars develop dense cores which must spin up during their formation, and tenuous envelopes which spin down as a consequence of their expansion. This implies large gradients in the angular velocity near the hydrogen burning shell. There, the shear instability can partly overcome the strongly stabilizing entropy and composition gradients, and briefly link hydrogen and helium burning layers. Rotation thus modifies the onion-shell picture of evolved stars — where the ashes of different burning stages are well separated by nuclear shell sources – and enables both matter and angular momentum to be transported through shell sources. Unusual nucleosynthesis may result.

Current models show that this shell penetration effect is most important at the outermost shell source, the hydrogen-helium discontinuity. Mixing through deeper, hotter shell sources turns out to be less efficient because of the short remaining life time of the star. We are thus left with three important phases of rotational mixing. The first is the mixing in the radiative envelope of massive stars. The other two may operate in stars of any mass – the mixing of protons downward into the helium burning layers, and the diffusion of ^{12}C upwards into hydrogen burning zones. In the following sections, these three different processes are discussed.

2 Rotational mixing during core hydrogen burning

During core hydrogen burning, massive stars consist of a convective core and a radiative envelope of several solar masses each. Detection of nuclear processed matter at the surface of these rapid rotators is strong evidence for rotationally induced mixing in their envelopes (Langer et al., 1996, and references therein). In a recent study, Heger (1998; see also Heger et al. 1998) computed the evolution of rotating massive stars in the mass range 8 to 25 $\mathrm{M}_{\odot}$. He used the the surface abundances of helium and CNO to calibrate the uncertain parameters of his mixing model. Although these abundances cannot be used as a verification of a model already calibrated to their production, the surface abundances of other isotopes produced or destroyed at different temperatures are predictions. For example, boron is destroyed at a relatively low temperature, (7×10^6 K) in massive stars. Such temperatures exist only one or two solar masses beneath the surface of massive main sequence stars. The rotating stellar models thus predict that rotational mixing first leads to a boron depletion at the surface, and that later during core hydrogen burning nitrogen is enriched (Fig. 1). This trend was also predicted by Fliegner et al (1996), who found observational support for this scenario in the boron and nitrogen abundances measured for main sequence B stars by Venn et al. (1996). They argued that the observed boron versus nitrogen abundance pattern could rule out the close binary mass transfer scenario as explanation for the majority of the enriched massive main sequence stars.

The rotational mixing of the envelope of massive main sequence stars also has important consequences for the nucleosynthetic yields of many isotopes. It can be easily understood that such mixing leads to the destruction of large amounts of the fragile light elements. For example, ^{3}He, which is found to be neither produced nor destroyed in non-rotating stars of $\sim 15\,\mathrm{M}_{\odot}$, almost completely disappears in rotating models (Table 1). As one expects this result to characterize all rapidly rotating main sequence stars — i.e., down to about $1.5\,\mathrm{M}_{\odot}$ — it may have important implications for the understanding of the chemical evolution of ^{3}He and for primordial nucleosynthesis (Olive et al. 1995). A further example is the dominant isotope of boron, ^{11}B. While ^{11}B is mostly destroyed during core hydrogen burning, even in non-rotating massive stars, rotation can reduce its production factor still further (cf. Table 1). However this decrease may be invisible against the large production of ^{11}B by the neutrino process (Woosley & Weaver 1995). The effect on the yields of the secondary CNO isotopes is roughly a factor two (Langer et al. 1996, Heger 1998). However, as discussed in greater detail in the next section, ^{15}N is particularly affected by rotational mixing after the main sequence.

Table 1: Comparison of various characteristic quantities of two rotating and two non-rotating models in the initial mass range 12...15 $M_\odot$. The sequences "KE12" and "KE15B" are computed with the KEPLER code assuming an initial equatorial rotation velocity of 200 km s^{-1}; note that different assumptions for the efficiency of the rotational mixing processes have been made (cf. Heger 1998, for details). Sequences "S135S7B" and "S145S7B" are also computed with the KEPLER code (cf. Woosley & Weaver 1995) and do not contain rotation or mass loss. The Table gives, from top to bottom, the initial mass and rotational velocity, the factor α_μ describing the efficiency with which mean molecular weight barriers slow down the rotational mixing (cf. Heger 1998), the masses of the star and the helium-, C/O-, and iron core at the time of core collapse, the rotation frequencies of the surface and the iron core at this time, the final logarithmic ratios of C/N and C/O with respect to their initial ratios, the final surface $^{12}C/^{13}C$ ratio, the production factors — defined here as output versus input — for selected isotopes, and an estimate $n'_{\rm cap}$ of the value of $n_{\rm cap}$ in the helium core, i.e., the average number of neutron captures per iron seed nucleus.

	KE12	KE15B	S135S7B	S145S7B
$M_{\rm i}$ / $M_\odot$	12	15	13.6	14.6
$v_{\rm rot,i}$/ km s^{-1}	200	200	0	0
α_μ	0	0.05	-	-
$M_{\rm f}$/ $M_\odot$	10.1	13.3	13.6	14.6
$M_{\rm He}$/ $M_\odot$	3.67	3.78	3.75	4.12
$M_{\rm C/O}$/ $M_\odot$	2.33	2.11	2.06	2.31
$M_{\rm Fe}$/ $M_\odot$	1.39	1.52	1.43	1.51
$\omega_{\rm env,f}/s^{-1}$	9.8 10^{-11}	6.3 10^{-10}	0	0
$\omega_{\rm Fe,f}/s^{-1}$	0.90	0.90	0	0
$[{\rm C/N}]_{\rm surf,f}$	-1.11	-1.08	-0.68	-0.69
$[{\rm C/N}]_{\rm surf,f}$	-0.50	-0.48	-0.13	-0.13
$(^{12}{\rm C}/^{13}{\rm C})_{\rm f}$	6.05	3.74	17.1	16.9
$f(^3{\rm He})$	0.07	0.01	1.13	1.10
$f(^{11}{\rm B})$	0.07	0.01	0.14	0.14
$f(^{15}{\rm N})$	2.82	4.44	0.38	0.38
$f(^{19}{\rm F})$	8.83	13.5	0.88	0.86
$f(^{22}{\rm Ne})$	1.51	1.91	3.49	4.05
$f(^{36}{\rm S})$	14.6	11.7	5.04	6.25
$n'_{\rm cap}$	4.5	4.3	1.4	1.8

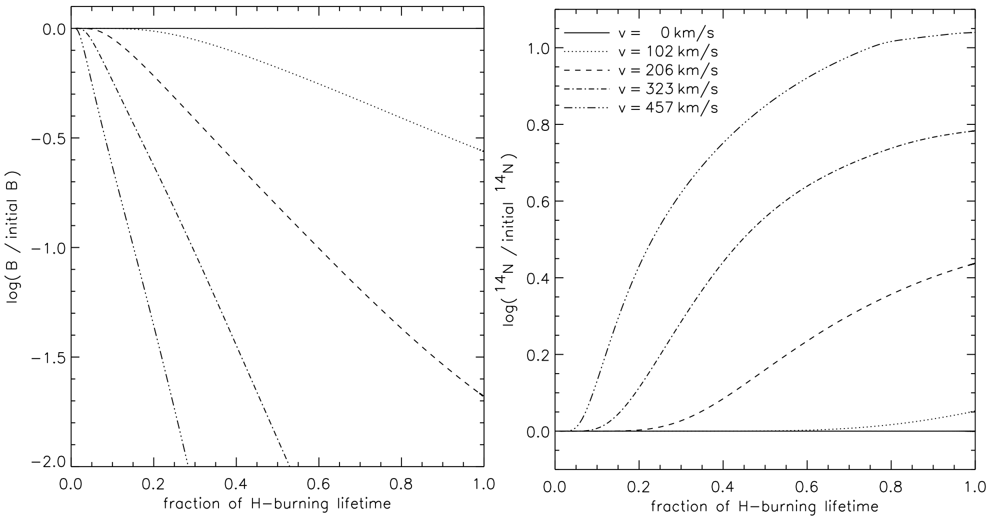

Figure 1: Two examples for changes of surface abundances as function of time during core hydrogen burning for 15 $M_\odot$ sequences which vary only in their initial rotational velocity. The left figure shows the surface mass fraction of boron ($^{10}B+^{11}B$); the right figure, the surface nitrogen mass fraction. The solid line corresponds to a non-rotating model where the surface abundances remain unaltered. The correspondence of other line styles with initial rotational velocities can be read off the legend in the right figure.

3 Mixing of protons into helium burning layers

Just as rotation aters 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 can be opened in the situation where this mixing can transport the products of one burning phase to the site of a neighboring one. This remains difficult, as neighboring burning stages are usually separated by large entropy and mean molecular weight differences. However, we have identified two situations where the entropy difference between the proton-rich and the helium burning layers is small: the late burning stages of massive stars during which the H-burning shell may extinct, and stars of very low metallicity where shell hydrogen burning occurs at very high temperature. In both cases, protons can be transported downward and be injected into the helium burning shell source, together with some amounts of ^{14}N. This situation is demonstrated in Fig. 2 for a 20 $M_\odot$ star with a metallicity of 2%.

The nucleosynthesis that occurs when protons are injected into helium burning has been analyzed in a parametric study by Jorissen & Arnould (1989). In fact, they predicted what we have now found in the helium shells of our rotating models, namely the production of substantial amounts of ^{15}N and ^{19}F. Fig. 3 shows that, independent of the efficiency factor α_μ, the ^{15}N abundance becomes more than 30 times its initial value, while fluorine is increased by a factor of almost 100. This composition, i.e., an $^{14}N/^{15}N$-ratio of ~ 20, may be related to the so far unexplained anomalous isotopic composition of the meteoritic "X-grain" (Hoppe et al. 1994).

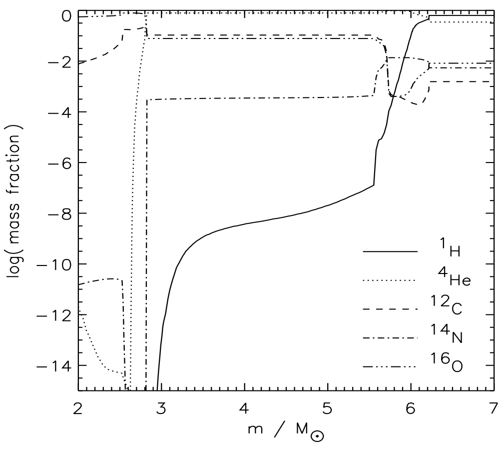

Figure 2: Mass fractions of ^{1}H, ^{4}He, ^{12}C, ^{14}N, and ^{16}O at the onset of core collapse in a $20\,\mathrm{M}_\odot$ model with an initial equatorial rotational velocity of 200 km s^{-1}, as a function of the mass coordinate m. Note that the proton mass fraction exceeds 10^{-7} at the outer edge of the convective helium burning shell ($m = 5.6\,\mathrm{M}_\odot$) and remains at about 10^{-8} in the major part of the shell.

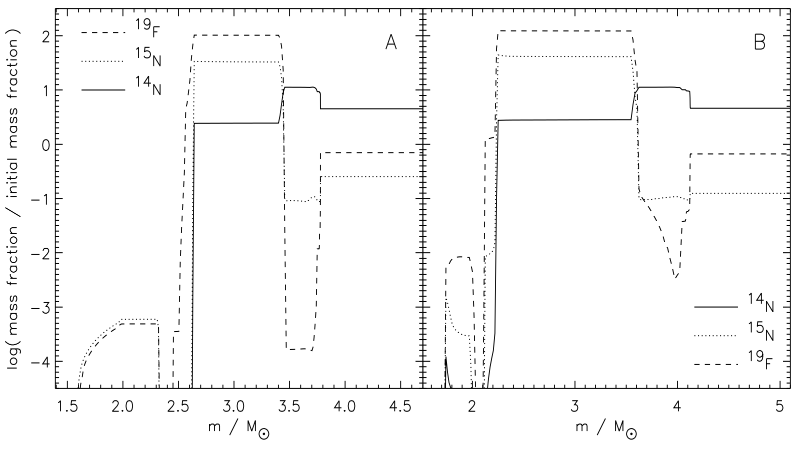

Figure 3: Mass fractions of ^{14}N (solid lines), ^{15}N (dotted lines), and ^{19}F (dashed lines) relative to their initial values, as function of the mass coordinate m from the edge of the iron core to some point within the convective envelope, at the time of core collapse in the model sequences “KE12” (Panel A) and “KE15B” (Panel B); cf. Table 1).

Furthermore, the enrichment of ^{15}N and ^{19}F in the helium shells of our models turns the total production factor (i.e., final versus initial amount of a specific isotope) from below 1 — i.e., net destruction — to values in the range 3...14 in the rotating presupernova models of 12 and 15 $M_\odot$ shown in Table 1. This means that, contrary to the conclusions of Woosley & Weaver (1995), this isotope can possibly be considered as a product of massive stars. This revised conclusion is consistent with the recent detection of ^{15}N in the Large Magellanic Cloud (Chin et al. 1998).

The effect of the mixing of protons into helium burning is not restricted to ^{15}N and ^{19}F. We also find a much stronger s-process in the rotating models compared to the non-rotating models of Woosley & Weaver (1995). This is reflected, for example, by the increased yield of ^{36}S, a product of the "weak" s-process in massive stars (Thielemann & Arnett 1985, Langer et al. 1989). It is also apparent in the reduced abundance of the secondary neutron source ^{22}Ne and the estimated (Heger 1998) number of neutrons captured per iron seed nucleus (Table 1).

The efficiency of the mixing of protons into helium burning environments as a function of the stellar mass, the metallicity, and the initial stellar rotation rate is something we will investigate elsewhere in the near future.

4 Mixing of carbon into hydrogen burning layers

As in the case where protons are mixed into helium burning layers, the mixing of helium burning products, especially ^{12}C, into hydrogen burning regions also gives non-standard nucleosynthesis. In both situations the first reaction to happen is ^{12}C(p,γ)^{13}N(β^+)^{13}C, but an ensuing α-capture is much more likely in a hot helium-rich region with few protons — i.e., when protons are mixed into the helium burning shell — while a second proton capture is more likely for the case when ^{12}C is mixed into proton-rich regions, thus giving rise to the formation of primary ^{14}N.

Note that, in a particular stellar sequence, the efficiency of mixing protons into helium burning layers and that of mixing ^{12}C into H-rich layers is not symmetric. In the models of the previous section, rotational mixing brings protons close to the upper end of the convective helium shell, but it is the growth of this shell which finally brings the protons into helium burning regions (Fig. 2). No ^{12}C is brought into hydrogen-rich layers by this process. For this to occur, the situation in stars in the initial mass range 8 to 12 $M_\odot$ may be more favorable. Those stars dredge-up part of their helium core by the deep penetration of the convective envelope. By imposing an artificial mixing on such a structure using a diffusion coefficient $D \propto (d\omega/dr)^2$ — which might, for example, correspond to a very rapidly rotating star, or to larger mixing efficiencies than what we mostly assumed — we obtained large amounts of primary ^{14}N in the the hydrogen burning shell.

Equally interesting, we also found a layer of several tenths of a solar mass just below the hydrogen burning shell that was strongly enriched in ^{13}C. This ^{13}C was formed through ^{12}C(p,γ) by protons from downwards diffusion and carbon mixed up from the helium burning layers. The proton concentration is small enough and the ^{12}C concentration large enough to avoid proton captures on ^{13}C to be efficient, and the temperatures are too low, in the hydrostatic burning phases, to allow α-capture on ^{13}C. In our particular example, the ^{13}C mass fraction reached only about 0.3%. Were it to become larger than ~1% — which is not implausible since we have not searched the parameter space for optimal conditions — these layers might become an interesting site for an r-process, or at least some fast neutron capture process. For this to happen, the relevant layers need to be located at a radius of not more than 10^{10} cm in order to achieve temperatures above $\sim 4\,10^8$ K for an explosion energy of 10^{51}erg — which, again, may be most likely in stars in the mass range 8 to 12 $M_\odot$. Note that this scenario could explain the observational evidence summarized by Mathews et al. (1992) and Wheeler et al. (1998) for the r-process in fact occurring in stars of this mass range.

Furthermore, the situation in low mass stars may be similar in several respects. In those stars which are known to generate the main s-process component using the $^{13}C(\alpha,n)$ neutron-source (Gallino et al. 1998), a ^{13}C-rich layer ("^{13}C-pocket") is required. This pocket does not form in standard stellar evolution calculations. Herwig et al. (1997) were in fact the first to self consistently generate a ^{13}C-pocket in AGB evolutionary models. They did so by assuming that diffusive mixing occurred between the He-burning shell and the H-rich envelope. Herwig et al. related their diffusive mixing to convective "overshooting". However, strong angular velocity gradients are likely to exist in the respective layers and the diffusion may well be due to shear mixing.

The appealing feature of this scenario is that, although the time scales for the r- and s-processes are vastly different, the idea of providing a ^{13}C-rich layer through rotationally induced mixing results in a unified picture for the generation of the neutron source in both cases. Certainly, our picture is speculative, but we believe that it worthy of serious investigation in the near future.

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