Nucleosynthesis in massive stars

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Abstract. In this paper we discuss recent theoretical results about nucleosynthesis in massive stars. First, we outline that rotation is able to alter the evolution and the chemical yields of massive stars substantially. Current models predict furthermore that the collapsing core which initiates typical Type II supernova explosions reaches critical rotation during the collapse. We then discuss the effects of a close binary partner on the nucleosynthesis yields of massive stars. Most important, we find that the output of radioactive ^{26}Al from secondary components of massive close binaries is so tremendous that it may dominate the Galactic ^{26}Al production.

1. Introduction

Massive stars — i.e. stars which explode as supernovae at the end of their evolution — are the main nucleosynthesis agents in galaxies. They produce the elements from oxygen through iron during their hydrostatic nuclear burning stages and final explosions (Woosley & Weaver 1995, Thielemann et al. 1996). They are also thought to synthesize the r-process nuclei beyond the iron group (cf. Qian *et al* 1998) and the weak s-process component (e.g., Langer *et al* 1989, Kaeppeler *et al* 1994), and they eject several radioactive chemical species into the interstellar medium (cf. Timmes & Woosley 1997), for example ^{26}Al which is detected in our Galaxy (Prantzos & Diehl 1996).

In the present paper we focus on two aspects of massive star nucleosynthesis which have long been neglected, i.e. the influence of rotation and the effect of a close binary companion. Rotation, which also affects the evolution of low mass stars (Pinsonneault 1997), can not only alter the chemical yields of massive stars but, by continuously mixing fuel into regimes of nuclear burning, can result in qualitatively new nucleosynthesis processes (Langer *et al* 1997a). Moreover, it may substantially affect the final collapse and supernova explosion. Massive close binaries, on the other hand, by shoveling matter from the primary component to the companion, disturb the order of nuclear burning phases as we know it from single stars. We shall show that sudden changes of the stellar mass can yield qualitatively new nucleosynthesis results.

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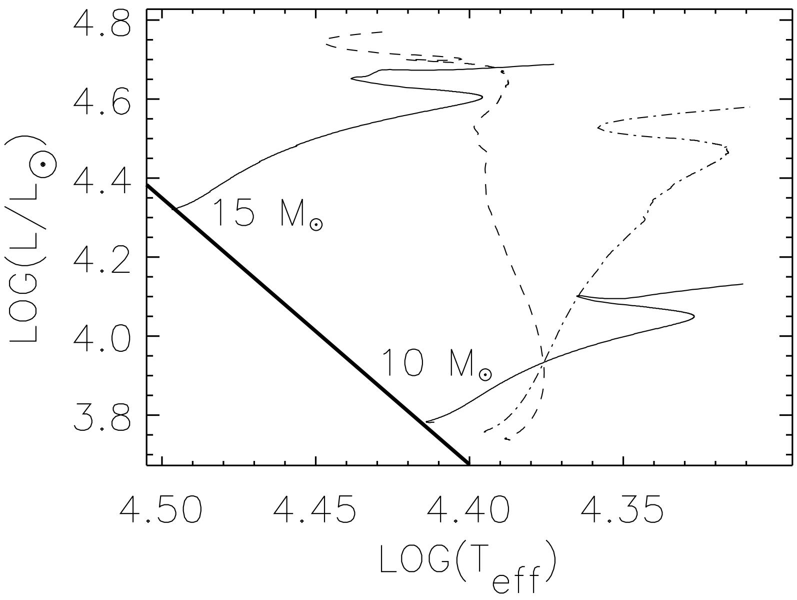

Figure 1. Evolutionary tracks of three $10\,M_{\odot}$ stars with different initial equatorial rotation velocities ($v_{\rm eq} = 0$, 280, and 400 km/s; solid, dash-dotted, and dashed lines, respectively) during the core hydrogen burning phase. The track of a non-rotating $15\,M_{\odot}$ star is also shown. The thick solid line marks the ZAMS position of non-rotating stars. (From Fliegner *et al* 1997).

2. Rotating massive stars

Rotation is a fundamental parameter of massive stars, affecting their evolution as strongly as initial mass and metallicity (Langer *et al* 1997b). Fig. 1 shows how rotationally induced mixing changes the evolution in the HR diagram during core hydrogen burning. Although the reduced effective gravity due to the centrifugal force leads to a smaller luminosity initially, rotational mixing between core and envelope results in a larger core mass and thus in a higher luminosity later on, compared to the non-rotating case.

An increased core mass has consequences for all subsequent burning stages, as the core mass determines which temperatures and densities are achieved in the course of stellar evolution. Since the cores contain the ashes of hydrostatic nuclear burning stages, the corresponding chemical yields of massive stars — e.g. that of oxygen — are increased by rotation (cf. Langer *et al* 1997a). However, while this effect can become of the order of tens of percent, also qualitative changes can be caused by increased core masses. An example is shown in Fig. 2, which compares the evolution of a non-rotating and a rotating $10\,M_{\odot}$ star in the $\rho_{\rm c} - T_{\rm c}$-diagram. While the latter evolves straight through all nuclear burning stages to become a Type II supernova, the non-rotating star ignites carbon in a degenerate core off-center and then cools and may become an ONeMg white dwarf (cf. Ritossa et al. 1996).

The physical processes responsible for the mixing of chemical species — besides convection predominantly Eddington-Sweet circulations and shear instabilities — do also transport angular momentum (cf. Pinsonneault 1997). As, in the course of stellar

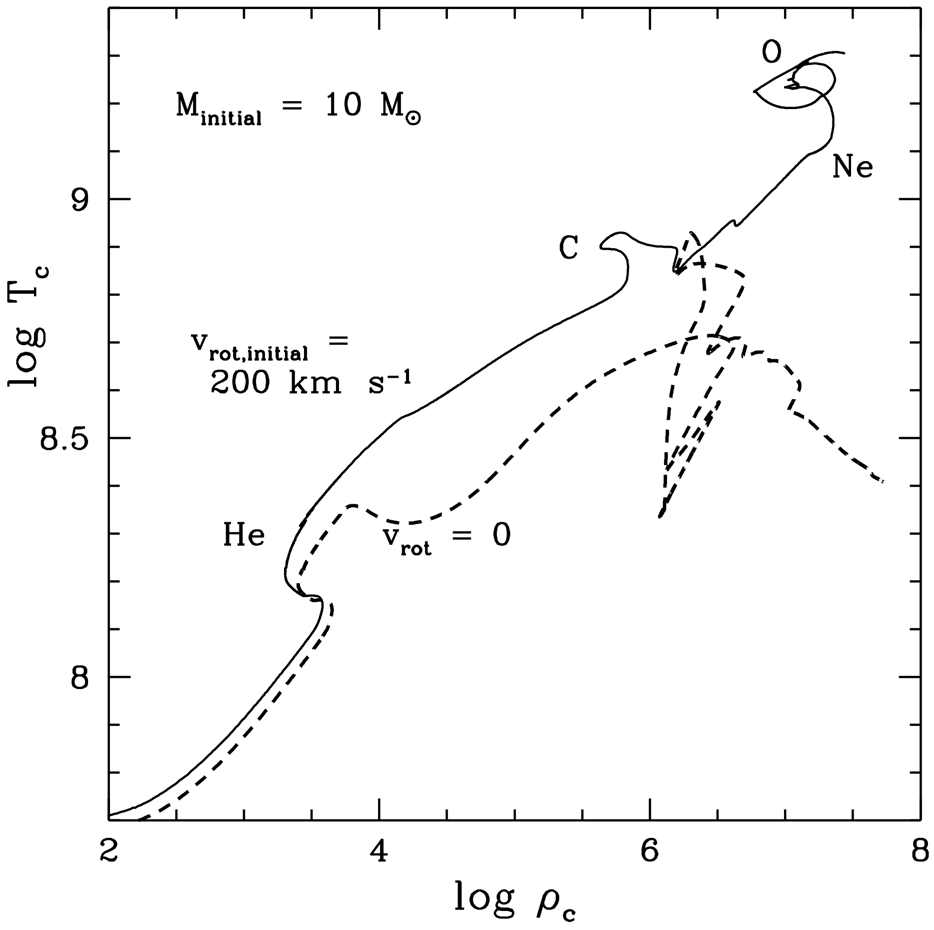

Figure 2. Evolutionary tracks of a rotating (solid line) and a non-rotating (dashed line) $10\,M_\odot$ star in the $\log \rho_c - \log T_c$–diagram. The various core burning stages are indicated along the track of the rotating model. (From Langer *et al* 1997a).

evolution, the cores contract and thus rotate more rapidly, the direction of angular momentum transport is usually from the core into the envelope. Furthermore, massive stars can lose angular momentum through stellar winds (Langer 1998). All of these processes need to be considered in order to obtain an estimate of the rotation rate of the core prior to its collapse. They were included in the recent study of the evolution of a $20\,M_\odot$ star from the zero age main sequence to iron core collapse by Heger *et al* (1998), who found that after core hydrogen exhaustion — i.e. after the ignition of the first nuclear shell source — the specific angular momentum of the core remains roughly constant (cf. Table 1). This has the consequence that the collapsing iron core (assuming local angular momentum conservation during the collapse) will reach critical rotation. This would, of course, have severe consequences for the core collapse supernova mechanism (e.g., Yamada & Sato 1994, Aksenov *et al* 1997).

However, the pre-supernova calculations of Heger *et al* (1998) are the first of its

Table 1. Properties of a $20\,M_\odot$ star at the mass coordinate $M_r = 1.7\,M_\odot$ (the mass of the iron core) at various times during the evolution (cf. Heger et al. 1998).

evol. stage	j cm^2/s	r cm	ρ g/cm^3	ω s^{-1}	ω/ω_c
ZAMS	10^{17}	$4\,10^{10}$	3.4	$7\,10^{-5}$	0.03
H-exh.	$2\,10^{16}$	$3\,10^{10}$	8.0	$2\,10^{-5}$	0.008
He-exh.	10^{16}	$3\,10^{9}$	$8\,10^{3}$	10^{-3}	0.01
collapse	10^{16}	$6\,10^{7}$	10^{9}	3	0.08
n-star	(10^{16})	10^{6}	$4\,10^{14}$	10^{4}	0.7

kind, and they should be considered as preliminary. Major uncertainties are due the poorly known influence of molecular weight gradients on the shear instability (cf. Maeder 1995, 1997) and our ignorance of the effect of magnetic fields in the stellar interior on the transport of chemicals and angular momentum (cf. Spruit 1998). If confirmed, the results above would have strong implications for Type II and Ib/c supernovae and the resulting neutron stars (cf. Langer et al. 1997a).

3. Massive close binaries

3.1. General Aspects

Most stars appear to be members of binary or multiple systems. The fraction of massive stars being members of *close* binaries — i.e. such in which mass overflow is expected to occur — is estimated to be of the order of 20...40% (cf. Garmany *et al* 1989, Podsiadlowski 1997, Mason *et al* 1998). Thus, it appears necessary to investigate the effect of binary mass transfer on the overall massive star nucleosynthesis yields: if the mass transfer would increase the yield of an isotope only by a factor of ~ 3, then massive close binaries might be the dominant source of this isotope.

Braun & Langer (1998) have studied the nucleosynthesis processes in typical massive close binaries. Fig. 3 gives an example of the evolution of a close $20 + 18\,M_\odot$ pair of Case A — i.e. mass transfer occurs during the core hydrogen burning phase of the primary (the initially more massive star) — in the HR diagram. Due to the transfer of most of the hydrogen-rich envelope of the primary to the secondary component, the primary becomes a helium star (cf. point D in Fig. 3) while the secondary evolves into a luminous blue supergiant. In both cases, the core masses evolve differently compared to single stars of the same initial mass (i.e., 20 or $18\,M_\odot$ in our example); the primaries' core masses are smaller, that of the secondaries larger.

Then, the primary may, as a helium star, develop strong Wolf-Rayet type winds mass loss (cf. Langer 1989ab, Woosley *et al* 1995), further reducing its helium core mass. This can affect the chemical yields of primary isotopes substantially, e.g. the carbon yield is enhanced at the expense of oxygen (cf. Langer & Henkel 1995). As long as the primary's helium core mass remains above $\sim 2\,M_\odot$ it will develop a collapsing iron core and become a supernova of Type Ib or Ic (Woosley *et al* 1995).

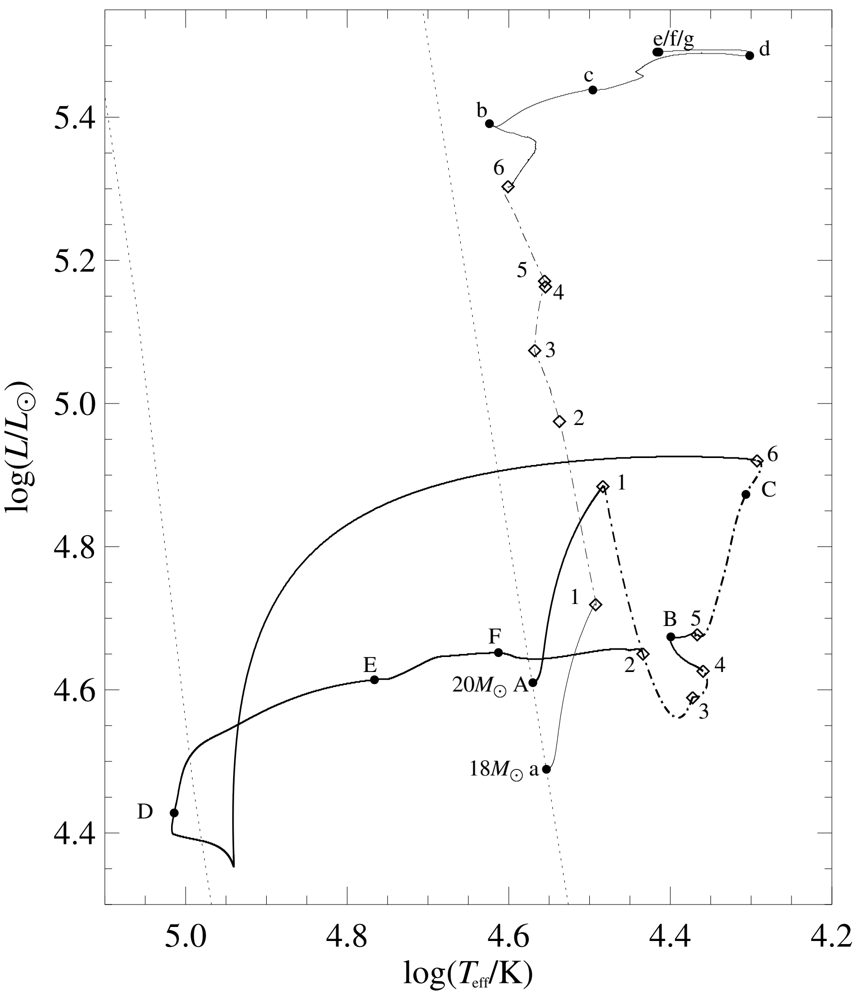

Figure 3. Evolutionary tracks in the HR diagram of the components of a 20+18 $M_\odot$ case A close binary system with a metallicity of $Z_\odot/4$ and an initial period of 2.5 days. The path of the primary component (initial mass 20 $M_\odot$) is marked by the thick line and upper case letters, that of the secondary by the thin line and lower case letters. Mass transfer stages correspond to the dot-dashed parts of the lines. The thin dotted lines designate the zero age main sequence and the location of pure helium stars (helium main sequence). The letters designate beginning and end of nuclear burning stages, i.e. core hydrogen burning (a/A – b/B), core helium burning (c/C – d/D), core carbon burning (e/E – f/F). g/G marks the beginning of core neon burning. Numbers designate mass transfer events for both stars. 1: beginning of Case A mass transfer, 2: maximum of mass transfer rate, 3: start of slow phase of Case A mass transfer, 4: end of Case A mass transfer, 5: start of Case AB mass transfer, 6: end of Case AB mass transfer. The final masses of the primary and secondary are 3 and 32 $M_\odot$, respectively.

As for the secondary star, which accretes the envelope of the primary during its core hydrogen burning evolution, it is a common assumption that it evolves after accretion exactly like a single star of the corresponding new mass ($\sim 32\,M_\odot$ in our example). However, Braun & Langer (1995) found that secondaries may retain significant structural differences compared to single stars, e.g. with the consequence that the supernova explosion occurs in the blue supergiant stage (cf. Fig. 3) — as in the case of the progenitor of SN 1987A — rather than in the red supergiant stage.

However, independent of this phenomenon, Braun & Langer (1998) found that substantial differences in the synthesis of secondary CNO isotopes do occur in the secondary components of massive close binaries, due to the interplay between CNO burning and so called thermohaline mixing. This mixing process does occur in the whole hydrogen-rich envelope of the secondary from the surface down to the convective H-burning shell since the star accretes helium enriched matter from the primary component (i.e. matter with a higher mean molecular weight is lying above matter with lower mean molecular weight). As the time scale for thermohaline mixing — which is for the first time treated as a time dependent process by Braun & Langer (1998) — and CNO processing at the bottom of the mixed zone are comparable, the production particularly of ^{13}C and ^{14}N is boosted in the whole H-rich envelope, increasing the yield of these isotopes by factors of the order of 2...3.

3.2. ^{26}*Aluminum*

The synthesis of ^{26}Al in secondary components of close binaries was found to deserve special attention. The reason is that for ^{26}Al, as it is β-unstable with a mean life time of $1.03\,10^6$ yr ($\tau_{1/2} = 7.2\,10^5$ yr), not only the amount which is synthesized matters, but also the time of the synthesis. As mentioned in Sect. 1, the γ-ray line emission from the decay of ^{26}Al in the Galaxy is observed. However, we can only see the decay of ^{26}Al nuclei in the interstellar medium; the decay inside stars is unobservable. Therefore, the ^{26}Al which is observed should either be produced during supernova explosions or shortly before. From the spatial distribution of the γ-ray line emission (Prantzos & Diehl 1996) we know that it originates from massive stars. Supernovae are in fact the currently favored production site, although the corresponding yields are very uncertain (Weaver & Woosley 1993, Thielemann *et al* 1996).

However, ^{26}Al is also produced during hydrostatic hydrogen burning, by proton capture on ^{25}Mg. Although very massive stars, through extremely strong stellar winds, can eject ^{26}Al generated during H-burning and contribute to the Galactic ^{26}Al (Langer *et al* 1995, Meynet *et al* 1997), the hydrogen burning contribution of less massive stars (say 10...30 $M_\odot$) is not considered as important (though see Langer *et al* 1997a) since the major fraction of the ^{26}Al decays inside the star before it is released in the course of the supernova explosion.

Braun & Langer (1998) found this to be different in massive close binary secondaries. Fig. 4 shows the time dependence of the amount of ^{26}Al generated by hydrogen burning in the interior of the secondary component of the 20+18 $M_\odot$ system shown in Fig. 3. Obviously, the ^{26}Al mass, although $10^{-5}\,M_\odot$ initially, would be of the order of $10^{-8}\,M_\odot$ at the end of the evolution if no mass accretion would occur. However, since fresh fuel — i.e. also fresh ^{25}Mg — is mixed into the core due to the mass accretion process (cf. Braun & Langer 1995) the amount of ^{26}Al is increased by orders of magnitude

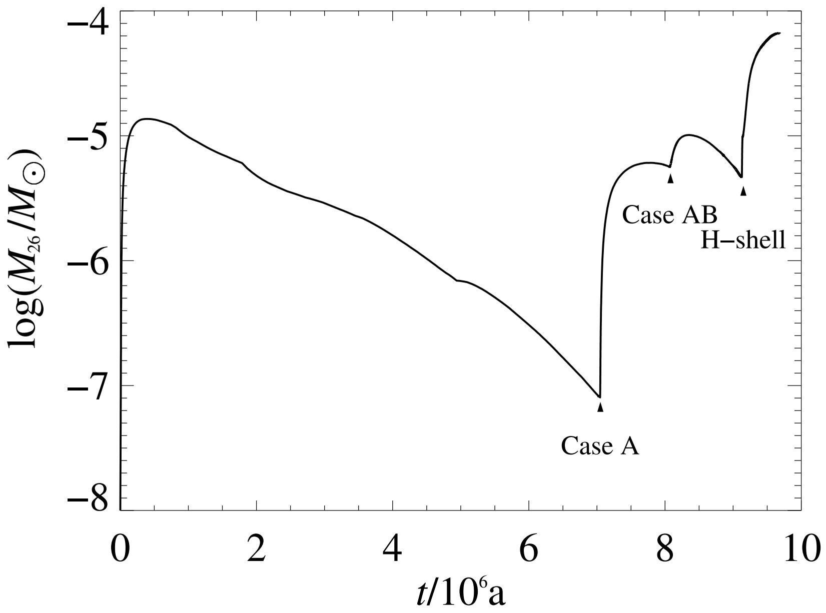

Figure 4. Evolution of the total mass of ^{26}Al inside the secondary component of a 20+18 $M_\odot$ case A close binary system (cf. Fig. 3) as a function of time (in 10^6 yr). The beginning of the Case A and Case AB mass transfer phase is indicated, as well as the beginning of hydrogen shell burning which marks the end of the core helium burning evolutionary phase. When the star explodes as a supernova of Type SN 1987A ($t = 9.68\,10^6$ yr) it contains almost $10^{-4}\,M_\odot$ of 26Al. Note that the initial metallicity of the stars is $Z_\odot/4$.

at that time.

This would already be sufficient to produce as much as $\sim 10^{-6}\,M_\odot$ ^{26}Al from this star of initially 18 $M_\odot$ — two orders of magnitude more than expected from single star calculations at $Z_\odot/4$ (cf. Langer *et al* 1995). However, we find the H-burning shell source in the secondary component to be much more efficient than in corresponding single stars. This leads to the coupling of an extended convection zone to the hydrogen burning shell, and consequently to the enrichment of the whole convection zone with ^{26}Al. In the end, our secondary star contains almost $10^{-4}\,M_\odot$ of ^{26}Al which will be liberated during the supernova explosion. As the chosen example appears to be a rather typical case, the Galactic ^{26}Al production may in fact be dominated by massive close binary systems.

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