# The Evolution of Surface Parameters of Rotating Massive Stars

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**Abstract.** We summarize the present status of the predictions of massive star models for the evolution of their surface properties. After discussing luminosity, temperature and chemical composition, we focus on the question whether massive stars may arrive at critical rotation during their evolution, either on the main sequence or in later stages. We find both cases to be possible and briefly discuss observable consequences.

## 1. Introduction

Massive main sequence stars are rapid rotators, with equatorial rotation velocities in the range of 100...400 $\mathrm{km\,s^{-1}}$ (Fukuda 1982, Penny 1996, Howarth et al. 1997). It is known since a long time that rotation can affect the stellar interior in several ways. *Rapid rotation* can reduce the effective gravity in the star, and it produces large scale flows (Eddington 1925). During the evolution, *differential rotation* occurs in all stars, with the possibility of the occurrence of various local hydrodynamic instabilities (cf. Endal & Sofia 1978, Zahn 1983) and corresponding mixing of chemical elements and angular momentum. Of relevance for massive stars are the shear instability (cf. Maeder 1997), the baroclinic instability (Zahn 1983, Spruit & Knobloch 1984), and the Solberg-Høiland and Goldreich-Schubert-Fricke instabilities (cf. Korycansky 1991).

Time dependent evolutionary models for massive stars including rotation have been constructed in the past in one dimension, using various degrees of approximation (e.g. Endal & Sofia 1978, Maeder 1987, Langer 1991, Talon et al. 1997, Langer 1998). Today, it is beyond reasonable doubts that the evolution of massive stars is influenced by rotation due to the physical mechanisms mentioned above (cf. also Fliegner et al. 1996). While the principle effects of rotation in the interior of massive stars during their evolution all the way to iron core collapse are described elsewhere (Langer et al. 1997a, Heger et al. 1998a), we concentrate here on observable surface parameters, i.e. (latitudal averages of) luminosity, effective temperature and surface abundances (Sect. 2), and equatorial rotation velocity. In particular, we discuss the question whether massive stars have the potential to evolve their surface to critical rotation, either during core hydrogen burning (Sect. 3) or beyond (Sect. 4).

## 2. Evolution of luminosity, surface temperature, and abundances

Fig. 1 displays the main effects of rotation on the initial position and evolution of massive stars in the HR diagram at the example of $10\,M_\odot$ tracks for various degrees of rotation (cf. Fliegner et al. 1996). First, the centrifugal force reduces the effective gravity in the stellar interior, i.e. the star appears to be less massive. Its luminosity and surface temperature are reduced (von Zeipel 1924, Kippenhahn 1977). The order of magnitude of this effect can be seen comparing the ZAMS positions of the $10\,M_\odot$ tracks.

However, during the further evolution of core hydrogen burning the effect of chemical mixing becomes dominant. Shear instability and Eddington-Sweet currents transport chemical elements synthesized in the stellar interior outwards, while the baroclinic instability smoothes out chemical gradients on equipotential surfaces. Due to the transport of helium into the envelope the average mean molecular weight of the star is increased compared to the non-rotating case, leading to much higher luminosities (Kippenhahn and Weigert 1990).

The effect on the surface temperature depends on the amount of mixing, i.e. on the degree of rotation. In the extreme case of chemically homogeneous evolution, the stars would evolve to the left of the ZAMS directly towards the helium main sequence (cf. Maeder 1987). However, more typical may be the case of moderate rotation in Fig. 1, which brings the star to cooler surface temperatures than the non-rotating models (cf. also Langer 1991). I.e., the main sequence band may be considerably widened due to rotationally induced mixing, which may make the requirement of "convective core overshooting" (Stothers & Chin 1992, Schroeder et al. 1997) obsolete.

In any case, Fig. 1 shows that even on the main sequence the stellar evolutionary track in the HR diagram depends on the initial rotation rate. I.e., rotation does not only have quantitative effects but qualitatively alters fundamental stellar characteristics as isochrones, the initial mass function, and mass-luminosity relations (Langer et al. 1997b).

A similar statement holds for the surface composition of massive stars: it is altered stronger for larger initial masses but also for larger initial rotation rates. In principle, all chemical species which are affected by proton captures at core hydrogen burning temperatures can show variations at the surface of rotating stars. However, as shown by Fliegner et al. (1996), the variations of different species do occur at different times. For example, boron is depleted very early during the main sequence evolution, while nitrogen and helium enrichments are achieved only much later. Fliegner et al. use B and N observations in B stars to show that the abundance pattern in massive early type stars (cf. Venn et al. 1996, and references therein) is in fact produced by rotational mixing and not by close binary interaction.

The time sequence of element abundance alteration is boron depletion, nitrogen enhancement together with carbon depletion, oxygen depletion, helium enhancement, and possibly sodium enhancement. The radionuclide $^{26}$Al may also be transported to the surface of rotating massive main sequence stars. For the effect of rotation on isotopic chemical yields of massive stars see Langer et al. (1997a).

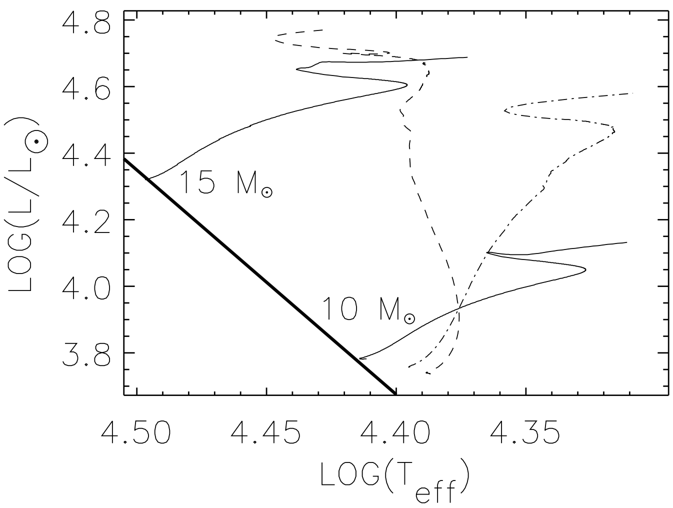


Figure 1. Evolutionary tracks in the HR diagram for non-rotating 10 and 15 $M_\odot$ stars (solid line), and a moderately (dashed-dotted) and rapidly rotating (dashed) 10 $M_\odot$ star, during the main sequence evolution. The thick solid line marks the ZAMS position for non rotating models (cf. Fliegner et al. 1996).

## 3. Evolution of the rotational velocity during core hydrogen burning

The evolution of the surface rotation rate of stars depends on three processes: the expansion or contraction of the star during its evolution, angular momentum redistribution due to the physical processes mentioned in Sect. 1, and the loss of angular momentum at the stellar surface.

During the main sequence evolution, the radius of massive stars increases by a factor of 2...3. In case the specific angular momentum would remain constant at the surface, the rotational velocity would decrease by that factor. However, according to Zahn (1994), rigid rotation is a good approximation for the angular momentum distribution of massive main sequence stars (however, see Maeder, this volume). In that case, the transport of angular momentum out of the convective core — which increases its density by a factor of 2...3 during core hydrogen burning — supplies angular momentum for the surface layers such that, as net effect, their rotational velocity remains roughly constant (e.g., Packet et al. 1980).

However, massive main sequence stars can lose angular momentum through a stellar wind, even in the absence of magnetic fields. The mechanism of this angular momentum loss is sketched in Fig. 2 for the case of rigid rotation; it works in the same way for differentially rotating stars provided that the time scale for angular momentum transport from the core to the surface is shorter than the mass loss time scale. Note that the effect of chemical evolution of the

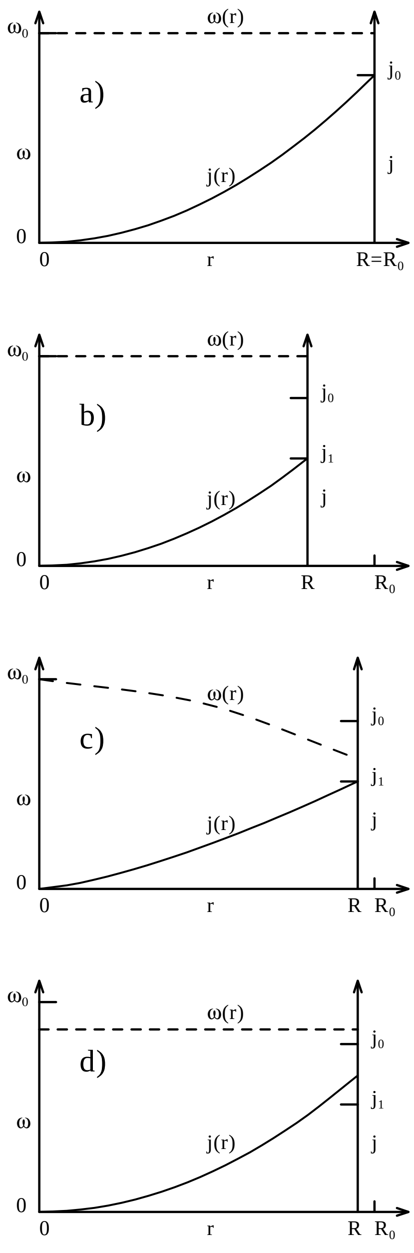


Figure 2. Schematic diagram of coupled mass and angular momentum loss in a rigidly rotating star, broken up into three discrete processes: mass loss without readjustment ($a) \to b)$); reexpansion of the star ($(b) \to c)$); and reestablishment of rigid rotation ($(c) \to d)$). $\omega$ is the angular velocity, $j = \omega r^2$ the specific angular momentum, and $R$ the stellar radius. Subscript 0 refers to the initial state.

star, which leads to an increase of the stellar radius with time, is neglected in Fig. 2.

Since stars of 10...20 $M_{\odot}$ lose only small amounts of their total mass during core hydrogen burning, they could be spun down only through magnetic winds. However, main sequence mass loss may be substantial for higher initial masses. Examining the evolution of 60 $M_{\odot}$ stars, Langer (1998) finds that massive main sequence stars may reach the $\Omega$-limit, i.e. the state of critical rotation, with the critical rotational velocity defined as to include the effect of radiation pressure (cf. Langer 1997). The considered stars may reach critical rotation not by spinning up but by a reduction of their critical rotational velocity as they evolve closer to the Eddington limit.

It is shown by Langer (1998) that massive main sequence stars may reach the $\Omega$-limit without catastrophic consequences. Only the mass loss rate is increased such that the corresponding angular momentum loss rate (cf. Fig. 2) ensures that the $\Omega$-limit is never exceeded. For a 60 $M_{\odot}$ star, mass loss rates of the order of $10^{-5}$ $M_{\odot}$ $\mathrm{yr}^{-1}$ are achieved at the $\Omega$-limit, resulting in a considerable spin-down. As the mass loss will not occur in a spherically symmetric wind but rather in a disk, and since it is unclear whether the stellar radiation can push all lost material to infinity (cf. Owocki & Gayley 1997), stars at the $\Omega$-limit might appear peculiar, perhaps like B[e] stars (Zickgraf et al. 1996).

## 4. Evolution of the rotational velocity beyond core hydrogen exhaustion

During the post main sequence evolution, strong chemical composition and entropy gradients at the location of the hydrogen burning shell source inhibit efficient mixing of angular momentum from the core into the hydrogen-rich envelope. Therefore, the angular momentum evolution of the latter can be — as first approximation — considered as independent of the core evolution (Heger et al. 1998ab).

Very massive stars may reach the $\Omega$-limit again immediately after core hydrogen exhaustion. While the opacity peak which brought them close to the Eddington limit on the main sequence is due to metal opacities, the peak due to helium ionisation becomes relevant for $T_{\mathrm{eff}} \lesssim 25\,000\,\mathrm{K}$. Since the stellar evolution proceeds more than hundred times faster in this phase, correspondingly higher mass loss rates have to be expected, with the result of a more eruptive phenomenon, perhaps resembling Luminous Blue Variables (García-Segura et al. 1997).

Heger & Langer (1998) found that also stars with masses below $\sim 20\,M_{\odot}$ may arrive at the $\Omega$-limit during their post-main sequence evolution. Stars in that mass range may undergo so called blue loops during core helium burning, i.e. excursions from the red supergiant branch into the B star regime. Since blue loops are connected to a decrease of the stellar envelope by roughly a factor of 10, a corresponding spin-up of the star may be expected. However, at the same time the structure of the hydrogen-rich envelope changes from convective to radiative. Heger & Langer showed that the assumption of rapid angular momentum transport in convective regions results in the fact that most of the angular momentum is retained in the convective outer part of the envelope as

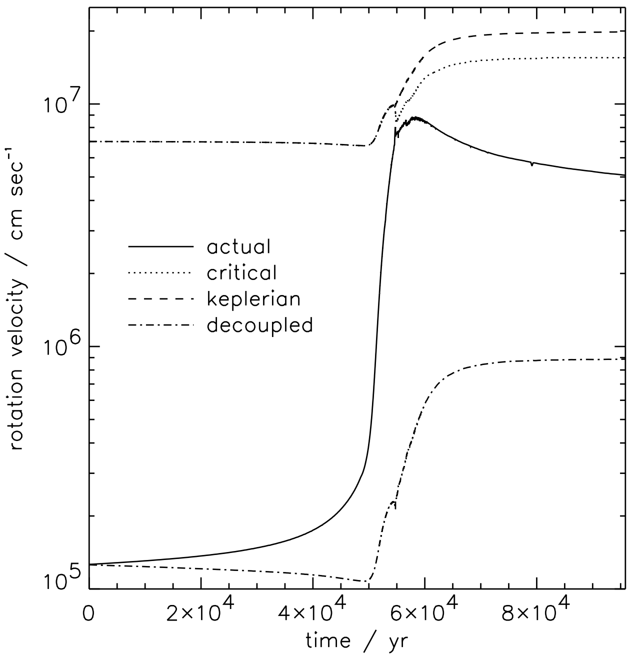


Figure 3. Equatorial rotation velocity as a function of time (solid line) of a rotating $12\,M_\odot$ model during the transition from the red supergiant branch to the blue supergiants stage during core helium burining ($t = 0$ is arbitrary). It is compared to the Keplerian (dashed line) and the critical rotation rate (dotted line); the latter two are different by the factor $1 - \Gamma$, $\Gamma$ being the Eddington factor. During the red supergiant phase it is $\Gamma \ll 1$ and the two lines coincide, while during the blue supergiant phase $\Gamma$ rises to 0.4. The dash-dotted line shows the evolution of the surface rotation rate if there were no angular momentum transport in the convective envelope (cf. Heger & Langer 1998).

the mass of this convective part decreases with time while retaining its spatial extent. Consequently, it spins up much more than if angular momentum were conserved locally.

Fig. 3 gives an impression of the order of magnitude of the effect. For the example of a $12\,M_\odot$ star, the rotational velocity is increased by a factor of 100 during the blue loop, where only a factor of 10 would be expected from the mere contraction. This is enough to bring the star to critical rotation, and only a mass loss enhancement and a correspondingly high angular momentum loss rate prevents the star from exceeding the $\Omega$-limit.

The consequence of this spin-up of contracting red supergiant envelopes is an episode of highly aspherical mass loss. Its consideration may be relevant for the interpretation of B[e] stars of rather low luminosity ($\sim 10^4\,L_\odot$, cf. Gummersbach et al. 1995), for the circumstellar material around blue supergiants (cf. Brandner et al. 1997) in general, and Supernova 1987A in particular (Woosley et al. 1997), and for post-AGB stars and the formation of bipolar planetary nebulae (García-Segura et al. 1998).

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