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 of 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 has long been known 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 doubt 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 principal 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. 1998), we concentrate here on observable surface parameters, i.e., (latitudinal averages of) luminosity, effective temperature, and surface abundances (Section 2), and equatorial rotation velocity. In particular, we discuss the question of whether massive stars have the potential to evolve their surfaces to critical rotation, either during core hydrogen burning (Section 3) or beyond (Section 4).

2. Evolution of Luminosity, Surface Temperature, and Abundances

Figure 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 & 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 shown 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. That is, rotation not only has quantitative effects, but qualitatively alters fundamental stellar characteristics such 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 more strongly 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 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 boron and nitrogen 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).

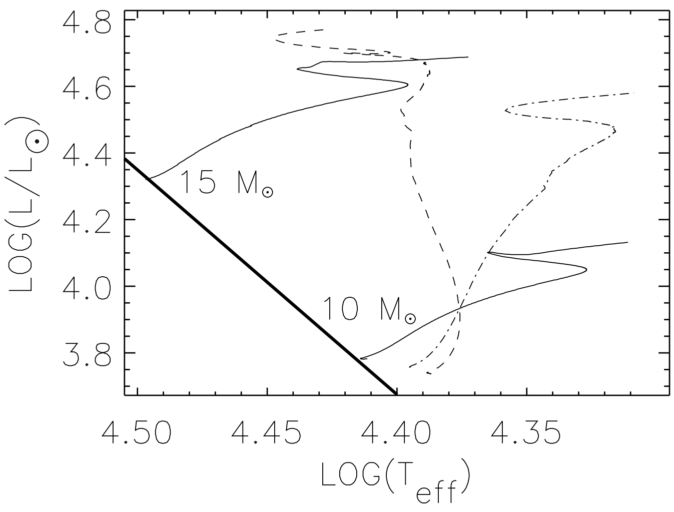

Figure 1. Evolutionary tracks in the HR diagram for non-rotating 10 and 15 $M_\odot$ stars (solid lines), and a moderately (dashed-dotted) and rapidly rotating (dashed) 10 $M_\odot$ star, during the main-sequence evolution. The thick solid line marks the ZAMS position for non-rotating models (cf. Fliegner 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 Section 1, and the loss of angular momentum at the stellar surface.

During main-sequence evolution, the radii of massive stars increases by a factor of 2–3. If the specific angular momentum remained 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 (see, however, Maeder 1998). 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 timescale for angular-momentum transport from the core to the surface is shorter than the mass-loss timescale. Note that the effect of chemical evolution of the star, which leads to an increase of the stellar radius with time, is neglected in Fig. 2.

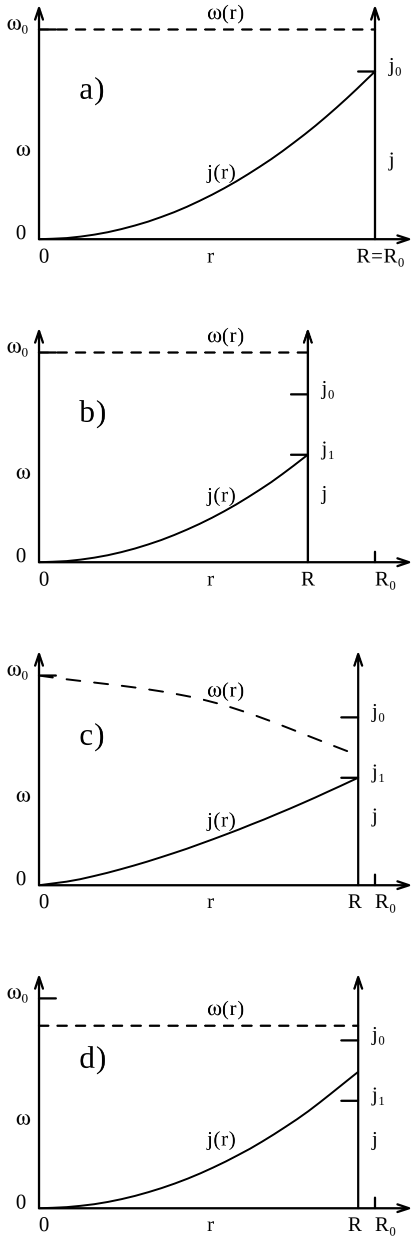

Figure 2. Schematic diagram of coupled mass and angular-momentum loss in a rigidly rotating star, broken up into three discrete processes: mass loss without readjustment [a)$\rightarrow$b)]; re-expansion of the star [b)$\rightarrow$c)]; and re-establishment of rigid rotation [c)$\rightarrow$d)]. ω is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

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 Ω-limit, i.e., the state of critical rotation, with the critical rotational velocity defined so as to include the effect of radiation pressure (cf. Langer 1997). The stars considered 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 Ω-limit without catastrophic consequences. Only the mass-loss rate is increased such that the corresponding rate of angular-momentum loss (cf. Fig. 2) ensures that the Ω-limit is never exceeded. For a 60 $M_\odot$ star, mass-loss rates of the order of 10^{-5} $M_\odot$ yr^{-1} are achieved at the Ω-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 Ω-limit might appear peculiar, perhaps like B[e] stars (Zickgraf et al. 1996).

4. Evolution of 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. 1997, 1998).

Very massive stars may reach the Ω-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 ionization becomes relevant for $T_{\rm eff} \lesssim 25\,000$ 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) also found that stars with masses below $\sim$20 $M_\odot$ may arrive at the Ω-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 most of the angular momentum being retained in the convective outer part of the envelope as 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.

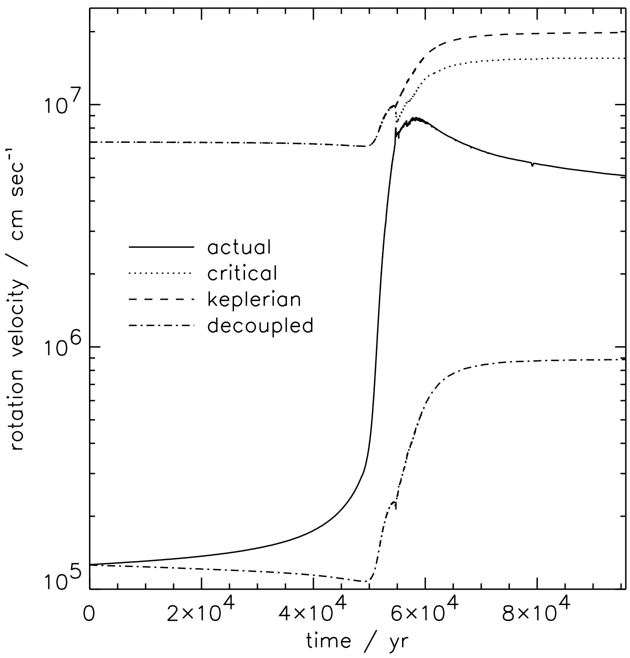

Figure 3. Equatorial rotation velocity as a function of time (solid line) of a model $12\,M_\odot$ rotating star during the transition from the red-supergiant branch to the blue-supergiant stage during core helium burning ($t = 0$ is arbitrary). It is compared to the Keplerian (dashed line) and the critical rotation rate (dotted line); these differ by a factor $1 - \Gamma$, with Γ the Eddington factor. During the red-supergiant phase $\Gamma \ll 1$ and the two lines coincide, while during the blue-supergiant phase Γ 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).

Figure 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 Ω-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 in general (cf. Brandner et al. 1997) 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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Discussion

Kudritzki: I have a very simple question: if the radius increases through stellar evolution, how can you have constant rotational velocity? Shouldn't the velocity become smaller as soon as the star starts to expand?
Langer: The reason is that the core contracts at the same time, and spins up, and so you develop a large gradient in angular velocity, which leads to a redistribution of angular momentum from the core to the surface. That helps the surface to keep this rotation rate.
Venn: Are you suggesting that all O and B stars that hit this Eddington limit and spin down go through an LBV phase?
Langer: Classically, we had the idea that we obtain LBVs from stars that hit the Humphreys-Davidson limit, basically. My idea is that we should replace it by the Ω limit, which of course depends on the rotation rate, and is not a constant for all stars. So we have LBVs well below the Humphreys-Davidson limit, which could not be explained with the classical Eddington limit, but which might be rapidly rotating stars; a slowly-rotating star could just go smoothly through the same region of the HR diagram and become a red supergiant.
Owocki: Well, Norbert and I have talked about this an awful lot, but I just wanted to make a comment for the record. I think one has to distinguish between two possible kinds of mass loss from the star. Norbert says that, from an interiors point of view, it is necessary for the star to lose a certain amount of angular momentum. We automatically think of mass loss as a mechanism – the Sun is a good example of that – and then we maybe think of a wind; but another way for a star to lose angular momentum is to shed a disk. So an alternative to the scenario put forward by Norbert is that, when a star gets close to its critical rotation rate it does indeed inflate up at the equator, but as it does so it gets

harder and harder to maintain the radiative driving there, because it's harder for the photons to make their way out along the major axis.

The key question is, can you then maintain rigid rotation as the equator extends. If you can, then at some point the outer part effectively goes into orbit, and maybe then you shed a disk. So the actual mass loss wouldn't be in the classical wind that we normal think of, but through some sort of decretion disk.

Langer: Let me just say, I don't want to be rude, but this is *your* problem! [Laughter.] The star has to get rid of some mass, otherwise it would hit the Ω limit, and I said here that the mass loss I need is a factor of 10 above the rate given by the theory of radiation-driven winds; so there are maybe other things going on. I don't say that the mass has to be taken away to infinity, it can stay somewhere in the environment – it just has to come off the star.

Owocki: Okay; one way we can distinguish these two things is to look at the nebulae carefully.

Gies: There has recently been some extensive work on projected rotational velocities of O stars – there's a paper by Howarth et al. in 1997 and one by Laura Penny in 1996. Laura made a very interesting plot of $v_{\rm e} \sin i$ against mass, and there's a large empty area in that diagram where there are no stars of high mass that are rapid rotators. So this might tie in with the idea that the more massive stars, which evolve rapidly, tend to slow down their rotation rather quickly.

Langer: Thanks for pointing that out; I'm eager to compare my results with observations.