Massive Star Evolution

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Abstract. The evolution of massive stars is far from being fully understood, as we outline by pointing to a number of open problems related to massive stars in the Magellanic Clouds. We argue that rotation may be a key ingredient in the physics of massive stars. We report on recent results obtained including rotation, and their relevance to the open problems described before.

1. Introduction: Current Problems in Massive Star Evolution

The quantitative theory of stellar structure is more than 100 years old (Emden 1907). Our understanding of the stellar interior has improved dramatically since then, especially so since it became possible to construct detailed stellar models with the help of computers, i.e., the 1950ies. Although still many fundamental questions are left in the field of low- and intermediate mass stars, we can say that their evolutionary path — i.e., their way from the main sequence through the red giant and asymptotic giant branch to the white dwarf stage — is know in detail since several decades (see, for example, Iben 1974). Also, the principles of the evolution of massive stars' cores through the major nuclear fusion stages from hydrogen to silicon burning are known for that long (Weaver et al. 1978).

However, even today our understanding of the evolution of the observable properties of massive stars ($M_{\rm ZAMS} \gtrsim 8\ \mathrm{M}_\odot, \log\ L/\mathrm{L}_\odot \gtrsim 4$) is still rudimentary, as demonstrated by the following six problems related to massive stars in the Magellanic Clouds, a list which is far from complete. 1) Where is the post-main sequence gap in the distribution of massive stars in the HR diagram of the LMC (Blaha & Humphreys 1989, Fitzpatrick & Garmany 1990)? It is predicted by *all* stellar evolution calculations (Fig. 9 in Langer 1991) but there is no trace of it in the data. Can this gap be filled by secondary stars in massive close binary systems (Fig.1)? 2) The observed trend of the blue-to-red supergiant

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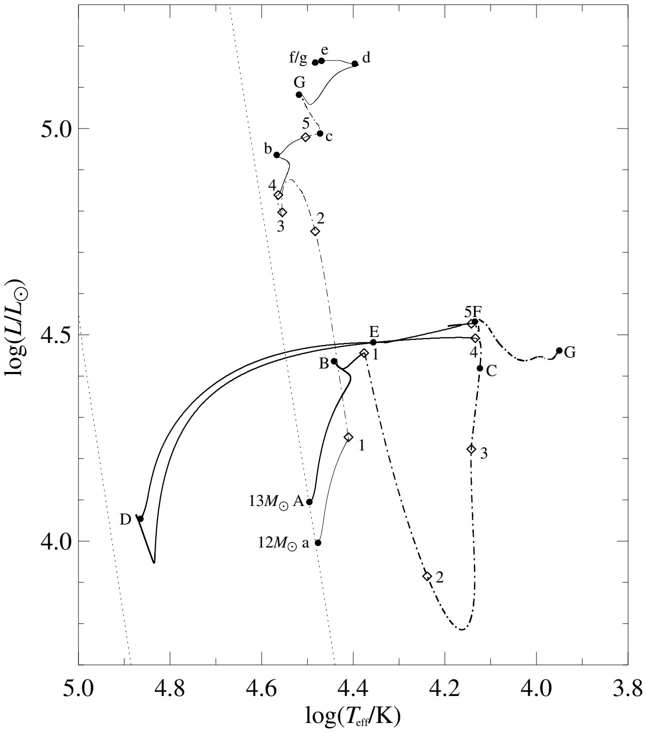

Figure 1. Evolutionary tracks in the HR diagram of the components of a 13+12 $M_\odot$ case B close binary system with a metallicity of $Z_\odot/4$ and an initial period of 3.1 days. The path of the primary component (initial mass 13 $M_\odot$) is marked by the thick line and upper case letters, that 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), and neon ignition (g/G). Numbers designate mass transfer events for both stars. 1: beginning of Case B mass transfer, 2: maximum of mass transfer rate, 3: start of slow phase of Case B mass transfer, 4: end of Case B mass transfer, 5: start of Case BB mass transfer. The final masses of the primary and secondary are 1.6 $M_\odot$ and 22 $M_\odot$, respectively. Note that this kind of binary evolution may be relevant to problems 1) and 3) mentioned in Section 1. See Braun & Langer (1999) for more details.

ratio as function of the metallicity is opposite to the one predicted by any stellar evolution models (Langer & Maeder 1995). 3) When in 1987 a *blue* supergiant exploded as a supernova in the Large Magellanic Cloud (Arnett et al. 1989) it was a surprise to the community. Until today, the reason for the blue color of the progenitor star is not unambiguously explained (see Langer et al. 1989, Woosley et al. 1998, and see Fig. 1). 4) What is the origin of the B[e] supergiants primarily found in the Magellanic Clouds (Gummersbach et al. 1995), i.e., how can evolved supergiants have disks or disk winds around them (Langer & Heger 1998)? 5) What is the evolutionary status of the WNL/Ofpe stars which again are primarily found in the Magellanic Clouds (Pasquali et al. 1997, Crowther & Bohannan 1997)? 6) Does the upper stellar mass limit depend on metallicity? While extremely massive stars ($\sim 200\,\mathrm{M}_\odot$) are found in the LMC (Kudritzki et al. 1996), recent investigations of stars near the Galactic Center (Figer et al. 1998) indicate the presence of very massive stars also in high metallicity environments.

The uncertainty in massive star evolution is dominated by the lack of understanding of two kinds of processes: the physics of mass loss from the stellar surface, and the physics of internal mixing processes (Langer 1994). In the present paper, we want to outline that both processes, despite acting in quite different locations in massive stars, may be strongly influenced by a process which has mostly been neglected in past studies of massive star evolution: rotation.

2. Massive star evolution with rotation

Massive stars are rapid rotators. Equatorial rotation velocities span the range $v_{\mathrm{rot}} = 100 - 400\,\mathrm{km\,s^{-1}}$, with B stars rotating closest to their break-up speed v_{crit}, and values of $v_{\mathrm{rot}}/v_{\mathrm{crit}} = \omega_{\mathrm{rot}}/\omega_{\mathrm{crit}} = 0.5$ frequently observed for O stars (e.g., Howarth et al. 1997). During the last decade, many observations have revealed unusual surface abundances that may require additional internal mixing (beyond that of plain convection) for their explanation (Langer et al. 1998, and references therein).

Fig. 2 gives an overview on the evolution of some surface properties of massive star models which include mixing due to rotationally induced instabilities and the effect of the centrifugal force. For the most massive models with the fastest rotation, one can even obtain a transition to Wolf-Rayet (WNL) type abundances (see also Langer 1992), which may be relevant for understanding the WNL/Ofpe stars (Pasquali et al. 1997). Furthermore, for a distribution of initial rotation rates, one obtains, at a given initial mass, a spread in main sequence luminosities and effective temperatures (Fig. 3). This might reduce the problem of the missing post-main sequence gap mentioned above, but seems not to solve it completely.

Rotation also increases the stellar mass loss rate (Langer 1998), which appears to be required by observations (Meynet et al. 1994). The anisotropy of the wind of rotating massive stars (Bjorkman & Cassinelli 1993) may also be related to the B[e] phenomenon (Langer & Heger 1998), to the bipolarity of LBV nebulae (Langer et al. 1999a), and perhaps to the rings around SN 1987A (Heger & Langer 1998).

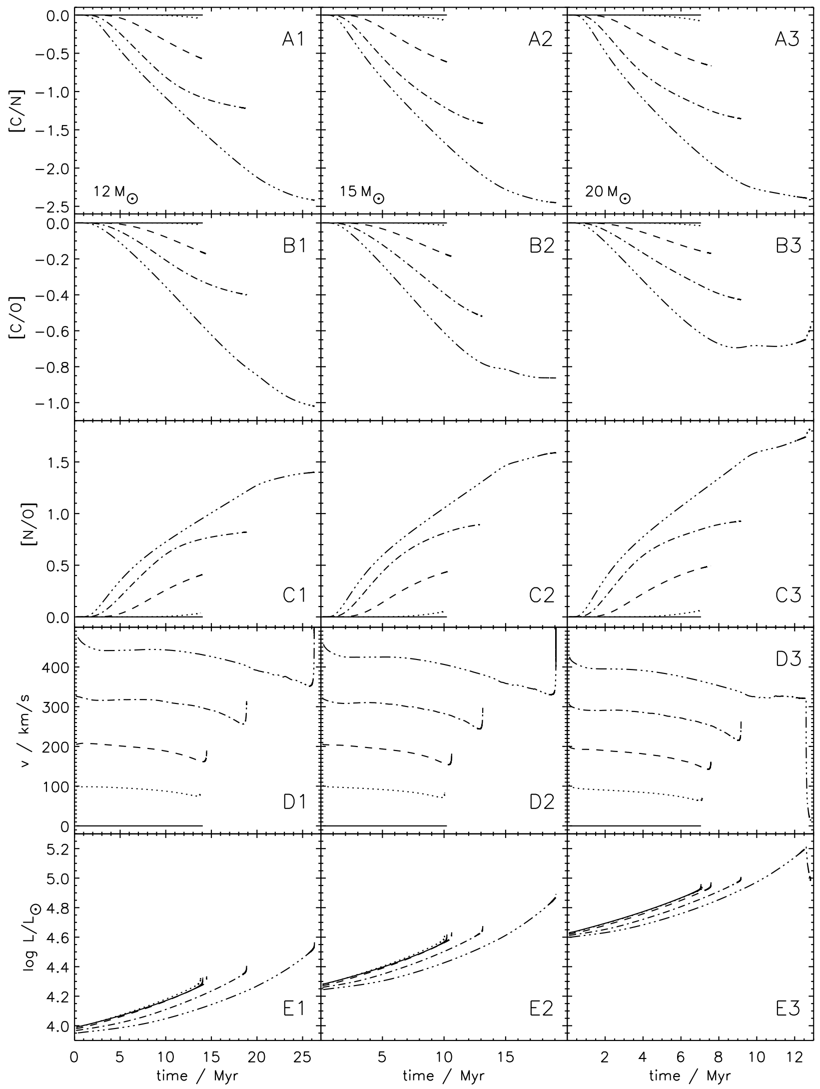

Figure 2. Evolution of surface properties of stellar models with rotation for initial masses of $12\,\mathrm{M}_\odot$ (left panel), $15\,\mathrm{M}_\odot$ (middle panel), and $20\,\mathrm{M}_\odot$ (right panel) and various initial rotation rates (no rotation: solid lines, about 100, 200, 300, 450 $\mathrm{km\,s^{-1}}$: dotted, dashed, dash-dotted and dash-triple-dotted lines, respectively) as function of time throughout core hydrogen burning. Shown are the the logarithmic increment of surface abundance ratios with respect to the solar ratio, the equatorial rotational velocity, and the stellar luminosity (see Heger 1998, and Heger et al. 1999 for more details).

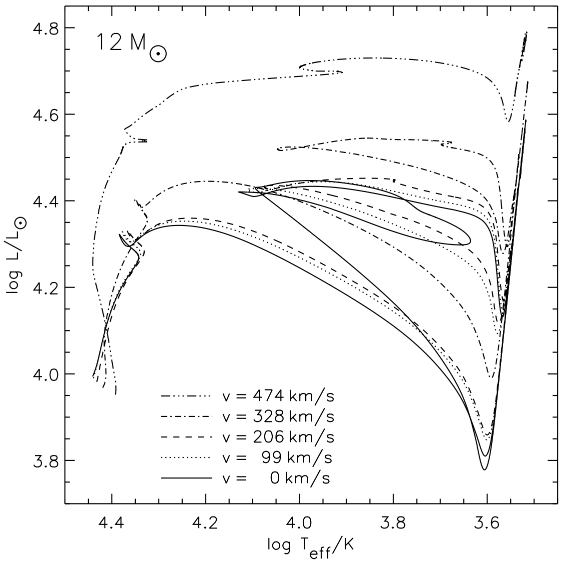

Figure 3. Evolutionary tracks in the HR diagram from the zero age main sequence to the pre-supernova position, for $12\,M_\odot$ stars with initial equatorial rotational velocities of $0\,km\,s^{-1}$, $99\,km\,s^{-1}$ (dotted line), $206\,km\,s^{-1}$ (dashed line), $328\,km\,s^{-1}$ (dash-dotted line), and $474\ km\,s^{-1}$ (dash-triple-dotted line). See Heger (1998) and Heger et al. (1999) for more details.

In summary, rotation has the potential to assess most of the problems mentioned in Section 1 (see also Talon et al. 1997, Maeder 1999). It certainly needs to be considered in the context of star formation, which is the process determining the initial angular momentum in a star (possibly in relation with problem 6; Figer et al. 1998) and its distribution function. However, rotation has further implications than those outlined here, for nucleosynthesis (Langer et al. 1999b), supernova explosions and pulsar rotation (Langer et al. 1999c, Heger et al. 1999), and even γ-ray bursters (MacFadyen & Woosley 1999)

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