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Modelling massive stars with mass loss

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Abstract

Mass loss plays a major role in the evolution of massive stars. Its effects on the modelling of massive stars (in particular internal structure, evolutionary tracks in the HR diagram, lifetimes, and surface abundances) will first be presented in detail. The modelling of Wolf-Rayet stars will then be examined. The interaction between mass loss and rotation, as well as between mass loss and pulsation, will finally be briefly discussed.

Introduction

Massive stars are stars with an initial mass larger than about 9 $M_\odot$. These stars are especially interesting since they strongly influence the spectral and chemical evolution of galaxies. They are indeed the main nuclear reactors forming the heavy elements, as well as the main source of UV radiation. These stars are characterized by a high temperature to density ratio leading to a high radiation to gas pressure ratio. This of course favours mass loss by stellar winds, which plays a major role in the evolution of massive stars.

To be able to include the effects of mass loss in a stellar evolution code, one needs some relation between the mass loss rates and the global stellar properties. A simple parametrization that has been very widely used in stellar evolution computations was given by de Jager et al. (1988). The mass loss rates increase with the luminosity and, at a given luminosity, increase when the effective temperature decreases. During the evolution of a massive star from the blue to the red part of the HR diagram, the mass loss rates will therefore increase and the effects of mass loss will become more and more important. Another important feature of the mass loss rates is the variation with the metallicity Z. The mass loss rates are indeed found to increase with the metallicity; this dependency can be simply parametrized as $\dot{M} \sim (Z/Z_\odot)^\alpha$ with $Z_\odot$ being the solar metallicity and α being between about 0.5 and 0.8 according to stellar wind models (Kudritzki & Puls 2000, Vink et al. 2001).

Evolution in the HR diagram

As a starting point to discuss the effects of mass loss in the HR diagram, we first consider the evolution of massive stars at constant mass. Evolutionary tracks at constant mass are shown for stars between 9 and 120 $M_\odot$ in Fig. 1 (left). For these models without mass loss, the main sequence band becomes wider when the mass increases, as a result of the larger convective cores of the more massive stars. The He-burning phase is found to form a kind of 'horn' in the HR diagram. Figure 1 (left) shows that most of this phase is spent in the blue part of the HR

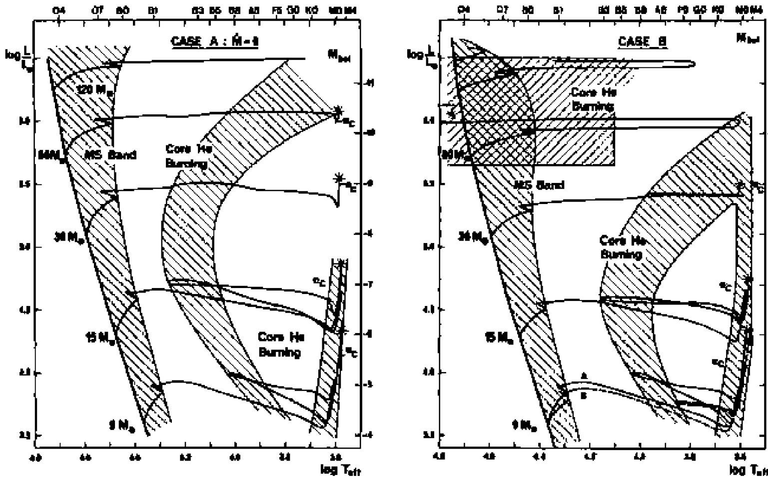

Figure 1: Evolutionary tracks in the HR diagram for stellar models computed without mass loss *(Left)* and with mass loss *(Right)*. Hatched areas correspond to the main phases of H and He burning. From Maeder (1981).

diagram (except for the most massive stars). This is due to the presence of an intermediate convective zone on top of an H-burning shell, which prevents the star from quickly evolving to the red part of the HR diagram (see e.g. Chiosi & Maeder 1986). Consequently, stellar models computed without mass loss predict almost no red supergiants for masses between about 20 and 50 $M_{\odot}$. This is of course in contradiction with observations, since many red supergiant stars are found in this mass range. Moreover, models at constant mass predict many red supergiants at very high luminosities, in contradiction with the observed upper limit distribution of luminous stars in the HR diagram known as the Humphreys-Davidson limit (Humphreys & Davidson 1979).

When the effects of mass loss are included in the computation, the luminosity of the star is reduced, as a result of the mass decrease. The star is nevertheless overluminous for its actual mass. Models including mass loss also exhibit larger core mass fraction, leading to a wider main sequence. The main sequence lifetime is found to slightly increase (by about 5 to 10%) when the effects of mass loss are taken into account. Figure 1 (right) shows the evolutionary tracks for massive stars computed with mass loss. Comparing HR diagrams computed with and without mass loss, one notes that the larger core mass fraction of models including mass loss lead to a wider main sequence. However, the main sequence becomes narrower for the most massive stars. By removing the surface layers of the star, mass loss leads indeed to a decrease of the envelope opacity. The stellar radius is therefore reduced and a blueward evolution is favoured. Concerning the He-burning phase, Fig. 1 (right) shows that there is a shift of the 'horn' to the red part of the HR diagram. This is due to the decrease or even the absence of an intermediate convective zone during the post main-sequence phase, resulting from the envelope reduction due to mass loss. Models with mass loss predict more red supergiants than without mass loss, in better agreement with the observations. For stars more massive than about 60 $M_{\odot}$, the effects of mass loss are very important and are able to remove the entire stellar envelope leaving a bare core: the star evolves to the Wolf-Rayet phase.

Wolf-Rayet stars

Wolf-Rayet (WR) stars are nice illustrations of mass loss effects on massive stars. These stars are characterized by high mass loss rates and strong emission lines with highly non-solar chemical abundances (see the recent review on the properties of WR stars by Crowther 2007). The WR spectra can be divided in two groups: the WN and WC stars. WN stars show products of the H-burning phase at their surface. For these stars, the HeII and N lines dominate the spectrum. WN stars can be subdivided in two groups: the late type WNL and the early type WNE stars. WNL are generally more luminous than WNE stars and contain some H contrary to WNE stars, which have no H left. WC stars show products of the He-burning phase at the surface. HeII, C and O lines dominate their spectra. They are also divided in late type WCL and early type WCE stars, with WO stars corresponding to extreme cases of WCE stars with higher O/C ratios.

In order to explain the abundance anomalies observed at the surface of WR stars, one has to find a mechanism able to efficiently remove the surface layers of the star. There are two main ways to form a WR star: through Roche lobe overflow in binary systems or through stellar wind losses in single stars. Figure 2 shows the typical evolution of the internal structure for a single massive star of 60 $M_{\odot}$. The removal of the external layers by stellar winds progressively reveals the internal layers. Near the end of the main sequence, the surface reaches layers that were initially in the stellar core. Products of H-burning can be observed at the surface and the star therefore becomes a WR star. During the post-main sequence phase of evolution, a H-burning shell is active. It then becomes inactive when its temperature decreases due to mass loss. The surface then reaches these layers resulting in a rapid decrease of the H abundance. The star evolves from WNL to WNE. As evolution continues, mass loss reveals layers that were in the He-burning core and enhancements of C and O are observed at the surface: the star becomes a WC star. The evolution of the surface chemical abundances of a massive star with mass loss can thus be briefly summarized as follows: first the initial abundances are observed at the surface. Then, intermediate abundances due to partial CNO processing with possible dilution effects are observed, before a phase of CNO equilibrium with the presence of H is reached. This phase is then followed by abundances of CNO elements at equilibrium but without H. Finally, products of He-burning are seen at the surface.

An important observational property of WR stars concerns the number frequency of WC stars with respect to WN stars, and in particular the variation of this number ratio with metallicity. Eldridge & Vink (2006) found that the variation of the WC/WN ratio with metallicity is very sensitive to the adopted mass loss rates during the WR phase. They showed that the observed relative population of WC to WN stars at different metallicities can be closely reproduced by using mass loss rates that scale with the initial metallicity during the WR phase. This scaling of the mass loss rates was first suggested by Crowther et al. (2002) from observations of WC stars, while Vink & de Koter (2005) showed how the mass loss rate is predicted to vary with initial metallicity for late type WC and WN stars. We thus see that standard models of massive stars with mass loss are able to correctly reproduce the variation of the WC/WN ratio. In the context of the transition between WN and WC stars, there is however another observational constraint that standard models are not able to reproduce: the number of WN/C stars. WN/C stars are transition stars between the WN and WC phase that are characterized by the simultaneous presence of both H- and He-burning products at the surface. While observations reveal that WN/C stars represent about 4% of the WR stars (van der Hucht 2001), standard models are not able to explain the existence of these stars because of the strong chemical discontinuity at the edge of the convective core in the He-burning phase. A smooth chemical transition is needed to produce the WN/C stars (Langer 1991).

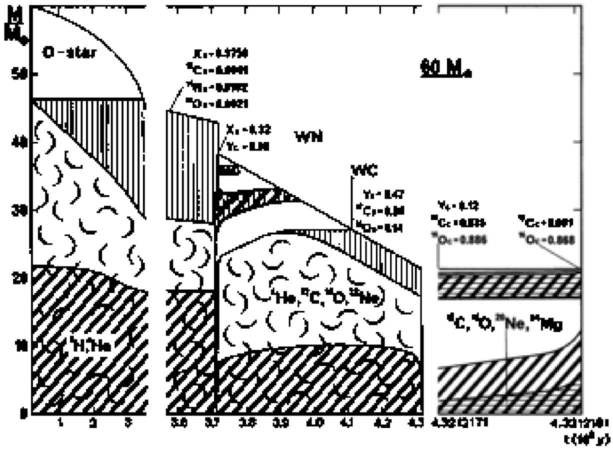

Figure 2: Evolution of the internal structure of a 60 $M_{\odot}$ star up to central C-exhaustion. Cloudy regions represent convective zones, heavy diagonals correspond to layers where the nuclear energy rates are larger than 10^3 erg g^{-1} s^{-1}. Vertically hatched areas indicate zones of variable H and He contents, while horizontally hatched regions correspond to zones of variable ^{12}C, ^{16}O, and ^{20}Ne contents. From Maeder & Meynet (1987).

Another important observational feature of massive stars is the number ratio of WR to O-type stars at different metallicities. Standard models with current mass loss rates are not able to reproduce these observations, since they severely underestimate the fraction of WR to O-type stars. A better agreement between theoretical predictions and observations can be obtained by increasing the value of the mass loss rates included in the computation (Meynet & Maeder 1994). This is due to the fact that higher mass loss rates increase the total lifetime in the WR phase and lower the value of the minimum initial mass required to form a WR star. These high mass loss rates are however in disagreement with recent determinations accounting for the effects of clumping in the winds of massive stars that suggest significantly lower values. We thus see that models including only mass loss do not predict a sufficient number of WR stars. To improve the situation, a first possibility is to account for the formation of Wolf-Rayet stars in binary systems. Models of massive star populations including mass transfer in binary stars are found to better reproduce the observed WR/O ratios by increasing the predicted number of WR stars (e.g. Eldridge et al. 2008). However, observational studies of WR populations in the Galaxy (van der Hucht 2001, 2006) and in the Magellanic Clouds (Foellmi et al. 2003ab) set some limit to the role of binaries in the formation of WR stars. These observations indeed reveal a fraction of WR stars in binaries of about 24%, 15% and 45% for the Galaxy, the Large Magellanic Cloud and the Small Magellanic Cloud, respectively. We thus see that binary mass transfer is an important channel for the formation of WR stars, but that binary evolution alone cannot explain all the observations. The effects of rotation and of enhanced mass loss due to Luminous Blue Variable (LBV)-like eruptions on the evolution of single massive stars have to be considered.

Interaction of mass loss with rotation and pulsation

Rotation is one of the key processes that have a strong impact on the physics and evolution of massive stars (see the review by Maeder & Meynet 2000). Mass loss and rotation interact in many ways. First, the evolution of rotational velocities of massive stars is sensitive to mass loss. The decrease of the rotation velocity of a massive star during its evolution is indeed found to be more efficient when the mass loss increases, due to the larger loss of angular momentum at the stellar surface. Secondly, rotation is found to change the mass loss rates. The line driven mass loss rates are indeed enhanced by rotation. Moreover, the mass loss rate per surface unit varies as a function of the colatitude leading to wind anisotropies induced by rotation. Mass loss of rotating stars can also be increased by reaching the critical limit or by surface chemical enrichments induced by rotational mixing. The latter process is especially important at low metallicity (see Maeder et al 2009).

In the context of WR stars, the inclusion of rotation in the models leads to many interesting results. Globally, rotation acts in two different ways. First, it increases the mass loss rates and favours the removal of the external layers. Secondly, rotational mixing brings He to the stellar surface, thereby favouring the appearance of the He bare core. Inclusion of rotation therefore results in an earlier entry into the WR phase. The WR lifetime, as well as the duration of the WNL phase, are then increased. Moreover, the threshold mass required to form a WR star is lowered by rotation. As a result, rotating models of WR stars are able to correctly reproduce the variation of the number ratio of WR to O-type stars with metallicity, as well as of the fraction of supernovae of type I_b/I_c to type II supernovae. Models including rotation also predict the existence of transition WN/C stars for initial masses between about 30 and 50 $M_\odot$, in good agreement with observations. However, these models are found to produce too many WN stars at solar and higher metallicities. Consequently, the observed WC/WN ratios can be correctly reproduced in the metal-poor region but not at solar and higher metallicities (Meynet & Maeder 2005). As discussed below, the evolution through the LBV phase and the associated strong enhancement of the mass loss rates may play an important role in shaping the WC/WN ratio.

Stars with initial masses above about 30 $M_\odot$ at solar metallicity may evolve into a LBV phase (see Cox & Guzik 2009). Observations of LBV stars show that during outburst phases very high mass loss rates can be reached. These outbursts, which are shell ejections rather than steady stellar winds, involve other processes in addition to the effects of the radiation pressure (Smith & Owocki 2006). In this context, pulsation and in particular strange mode instabilities may play a role (for more details about strange modes and instabilities, see Glatzel 2009 and Saio 2009). The LBV phase may also play a key role for populations of WR stars. As mentioned above, rotating models computed by Meynet & Maeder (2005) predict too low values for the WC/WN ratio at solar and higher metallicities. In these computations, it was assumed that a star entering the WR stage during the main sequence phase avoids the LBV phase. As discussed by Meynet et al. (2008), this hypothesis is probably not correct. A more realistic solution is to consider that a star becoming a WR star during the main sequence enters a LBV phase after the core H-burning phase, before evolving back into the WR regime. When this solution is applied to rotating models, reasonable values for both the WR/O and the WC/WN ratios are obtained at solar metallicity. Both ratios are not reproduced by non-rotating models computed with the same hypothesis. Only the case at solar metallicity has been currently computed, but such a scenario is expected to lead also to results in good agreement with observations at other metallicities.

As seen before, the inclusion of mass loss results in a change of the global properties and internal structure of a stellar model and thereby modifies the pulsational properties of a star. This is nicely illustrated in the case of B supergiants for which oscillation modes are detected. For these stars, the presence of an intermediate convective zone seems to be required in order to correctly reproduce the observed oscillation frequencies (Saio et al. 2006). Interestingly, the structure of this intermediate convective zone is very sensitive to many physical processes and in particular to the adopted mass loss rates (see Dupret et al. 2009 and Godart et al. 2009). Finally, we note that the observation of oscillations for WR stars are also very promising in order to improve our understanding of the modelling of massive stars. This has been recently illustrated by the detection of a pulsation period of 9.8 h in the star WR 123 (Lefèvre et al. 2005) and by the following theoretical studies aiming at correctly reproducing this observation (see Glatzel 2009).

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DISCUSSION

Baglin: The observational mass loss as a function of luminosity and temperature used in stellar modeling includes rotating stars and is based on average values. How do you take this into account in stellar modeling?

Eggenberger: We have indeed to account for the fact that the empirical values for the mass loss rates used for non-rotating stars are based on stars covering the whole range of rotational velocities. This is done by the convolution of the rotation effects on the mass loss rates over the observed distribution of rotational velocities, taking also into account that the orientation axes are randomly distributed. This leads to an estimated correction factor of about 0.8, which has to be applied to the mass loss rates for the main sequence OB stars.

Puls: (i) Regarding mass loss in the LBV phase, there is not only the possibility of inducing mass loss by strange mode-oscillations but there is also the possibility of very strong continuum driven mass loss which might be responsible for the giant outbursts (see the work by Owocki & Shaviv). (ii) You mentioned that the mass loss rates of O and WR stars in the evolutionary codes are described by certain scaling relations. One should point out, however, that there is a significant difference between both. For O stars, the mass loss seems to be fairly understood, and theoretical and observed scaling relations agree quite well. For WR stars, there are "only" observed relations, with a significant scatter if compared to individual objects. Even worse, there are almost no theoretical "self-consistent" models of WR winds (except for one model by Gräfener et al. which is not very representative). Thus, in particular the Z-dependence of WR winds cannot be considered as really understood.

Noels: If the mass loss rate is decreased by a factor 3 to 10, is it still possible to form a WR star from the evolution of a single massive star, from a theoretical point of view?

Meynet: Mass loss during the O-type star phase is a key parameter for deciding when a star is into the WR phase and therefore its duration. Lower mass loss will delay or even prevent the star from becoming a WR star. In case very low mass rates for O-type stars would be confirmed then, one will be obliged to consider other possibilities: WR formation through RLOF in close binary systems, or fast rotation, or heavy mass loss in other phases of evolution. However it has to be checked for all these possibilities if they can account for the observed variations with the metallicity of the WR/O, WN/WC number ratios.