Massive star evolution: What we do (not) know

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The modelling of massive star evolution is a complex task, and is very sensitive to the way physical processes (such as convection, rotation, mass loss, etc.) are included in stellar evolution code. Moreover, the very high observed fraction of binary systems among massive stars makes the comparison with observations difficult. In this paper, we focus on discussing the uncertainties linked to the modelling of convection and rotation in single massive stars.

1 Introduction

The modelling of massive star is a complex task, involving a variety of physical processes. Among the required ingredients of all stellar evolution codes are the treatment of the heat transfer in convective and radiative zones, the nuclear reaction network, the equation of state, the computation of opacities, and the inclusion of mass loss (e.g. Kippenhahn & Weigert, 1990; Maeder, 2009). During the past two decades, a variety of other processes were progressively added, such as rotation (Endal & Sofia, 1976; Zahn, 1992; Maeder & Zahn, 1998), transport of angular momentum and chemical species by internal magnetic fields (Spruit, 2002; Maeder & Meynet, 2003) or by internal waves (e.g. Kumar & Quataert, 1997; Talon et al., 2002; Talon & Charbonnel, 2003; Fuller et al., 2014). Moreover, massive stars are often found in multiple systems (e.g. Sana et al., 2012), and their modelling requires in addition the treatment of tidal interactions, Roche-lobe overflow, common envelope evolution and merging (see the review by Langer, 2012).

Each of these processes suffers from uncertainties in the way they should be implemented in stellar evolution code. It leads to major uncertainties in our understanding of the evolution of massive stars, particularly of the post-main-sequence evolution (Martins & Palacios, 2013; Chieffi & Limongi, 2013; Georgy et al., 2014a). In this paper, we focus on discussing some of the uncertainties linked to the modelling of convection and rotation in single massive stars.

2 The modelling of convection in the interior of massive stars

Convection is ubiquitous in massive star evolution (see Fig. 1): successive convective cores ("CC") are often linked to one of the burning stages. After the main-sequence (MS), nuclear burning may also occur in convective shells ("CS"), producing a complex
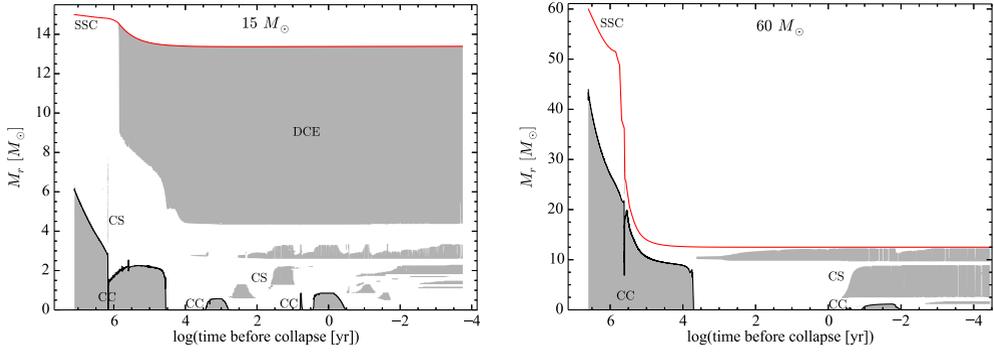
Fig. 1: Convective structure of solar metallicity 15 $M_\odot$ (left) and 60 $M_\odot$ stellar models (right). The horizontal axis shows the time left until the star collapses. The vertical axis is the mass coordinate (so-called "Kippenhahn diagram"). The shaded area represent the convective zones inside the star. The labels are for sub-surface convection ("SSC"), convective core ("CC", highlighted by the thick solid black line), deep convective envelope ("DCE"), and convective shell ("CS"). The thick line indicates the surface of the star.

structure during the very late stages of the evolution. During the MS, a very tiny convective zone is present near the surface (Maeder et al., 2008; Cantiello et al., 2009). Finally, for stars evolving in the red part of the Hertzsprung-Russell diagram (HRD, typically the stars having a red supergiant phase), a deep external convective envelope ("DCE") develops. This highlights the need for a correct modelling of convection in massive star models.

In most of stellar evolution codes, convection is modelled in two steps:

1. The position of the convective zone boundaries are determined according to the Schwarzschild or Ledoux criterion (see e.g. Kippenhahn & Weigert, 1990).

2. Inside the convective zone, the thermal structure is computed by computing a thermal gradient. This can be done in several ways: by assuming that convection is purely adiabatic, by using the "Mixing-Length Theory" (MLT, Böhm-Vitense, 1958) or more sophisticated models (see Viallet et al., 2015, and references therein).

The sizes of the convective cores obtained in this way are known to be too small with respect to observations for a long time (e.g. Maeder, 1975), and need to be artificially extended by an arbitrary length: the "overshoot". This overshoot cannot be predicted by design in the framework of the MLT. In stellar evolution codes, the overshoot is usually considered to be "penetrative" (Zahn, 1991, where the core is extended by a constant fraction of the pressure scale height at the edge of the core), or "diffusive", with a diffusion coefficient calibrated on observations or numerical simulations (Freytag et al., 1996; Herwig, 2000).

Both approaches contain free parameters, and thus need to be calibrated. This can be done in different ways, for example by reproducing the observed width of the MS (Ekström et al., 2012), or by fitting the drop of the surface velocities of stars when their surface gravity decreases (Brott et al., 2011).

On the other hand, the development of multi-dimension hydrodynamics codes and of computing power has allowed for simulations of convection in a variety of physical conditions from first principles: envelope of cool stars (e.g. Freytag & Höfner, 2008;

Chiavassa et al., 2009; Viallet et al., 2013; Magic et al., 2013), or deep convection during different evolutionary stages of star life (e.g. Meakin & Arnett, 2007; Couch et al., 2015; Woodward et al., 2015; Cristini et al., 2017; Müller et al., 2016; Jones et al., 2017).

Simulations of deep convection show that, at least during the advanced stages, convective boundaries are moving ("entrainment", see Meakin & Arnett, 2007). Moreover, there is a significant mixing across the boundary, making it less stiff than usually accounted for in 1d stellar evolution modelling (Cristini et al., 2017).

From observations, a similar result is obtained thanks to asteroseismology for the overshoot during the MS (see e.g. Moravveji et al., 2016). The modelling of variable blue supergiants seems to be a promising way of constraining convection is stellar models (Georgy et al., 2014a). In any case, it is clear that MLT is not able to correctly reproduce the behaviour of convective flows as seen in multi-d simulations, and there is an urgent need for a new way of treating convection in stellar evolution models (see Arnett et al., 2015).

3 The modelling of rotation in the interior of massive stars

The inclusion of rotation in 1d stellar evolution codes is not straightforward. Due to its (at least) 2d nature, several hypotheses and approximations are requested to treat rotation in 1d (process sometimes called "1.5d"). First of all, the star is described in the framework of the Roche model, assuming a spherical-symmetry gravitational potential on top of which the effects of centrifugal acceleration are added. Moreover, a strong horizontal turbulence is assumed inside the star, homogenising the angular velocity on an isobar ("shellular rotation", see Zahn, 1992; Maeder & Zahn, 1998).

In this framework, rotation has two main effects:

1. the centrifugal acceleration modifies the usual stellar structure equations by adding corrective terms in the momentum equation and radiative transfer equation (Meynet & Maeder, 1997).

2. thermal non-equilibrium produces large scale currents inside the star (the so-called meridional circulation, or Eddington-Sweet currents, Sweet, 1950). In turn, these currents transport angular momentum and chemical species, modifying the internal rotation of the star. Differential rotation can occur, generating shear turbulence.

The transport of angular momentum is modelled by the following relation (Zahn, 1992; Maeder & Zahn, 1998):

$$\rho\partial_t\left(r^2\bar{\Omega}\right) = \frac{1}{5r^2}\partial_r\left(\rho r^4\bar{\Omega}U_2\right) + \frac{1}{r^2}\partial_r\left(\rho D_v r^4\partial_r\bar{\Omega}\right), \tag{1}$$

where $\bar{\Omega}$ is the mean angular velocity on an isobar, U_2 is the radial component of the meridional circulation velocity, and D_v is the vertical turbulence diffusion coefficient. The expression of U_2 is complex and can be found in Maeder (2009).

The transport of chemical species can be modelled by a purely diffusive approach (Chaboyer & Zahn, 1992):

$$\rho\partial_t\left(X_i\right) = \frac{1}{r^2}\partial_r\left(\rho r^2\left(D_v + D_{\text{eff}}\right)\partial_r\left(X_i\right)\right), \tag{2}$$

where X_i is the abundance of the element i, and D_{eff} is the effective diffusion coefficient, accounting for the effect of meridional circulation: $D_{\text{eff}} = \frac{(rU_2)^2}{30D_h}$, where D_h is the horizontal turbulence diffusion coefficient.

3.1 The vertical turbulence

The diffusion coefficient D_v should account for any kind of turbulence arising in the vertical direction. Depending on which stellar evolution code is used, different effects are accounted for: secular shear instability (Maeder, 1997; Talon & Zahn, 1997), dynamical shear instability (e.g. Heger et al., 2000), Solberg-Hoiland instability (e.g. Heger et al., 2000), Goldreich-Schubert-Fricke instability (e.g. Heger et al., 2000; Hirschi & Maeder, 2010), Tayler-Spruit dynamo induced mixing (Spruit, 2002; Maeder & Meynet, 2003). Most of time, the corresponding diffusion coefficients are summed up. However, Maeder et al. (2013) propose a way to consider the combined effects of these instabilities at once.

3.2 The horizontal turbulence

As in the case for the vertical turbulence, several prescriptions can be found in the literature for the diffusion coefficient linked to the horizontal turbulence (Zahn, 1992; Maeder, 2003; Mathis et al., 2004).

3.3 Advection and diffusion or diffusion only?

As of today, we can distinguish two big families among the stellar evolution codes that contain the treatment of stellar rotation. The first of them solves the full equation for the transport of angular momentum (eq. 1): the Geneva stellar evolution code (Eggenberger et al., 2008), STAREVOL (Decressin et al., 2009), FRANEC (Chieffi & Limongi, 2013), ROSE (Potter et al., 2012)[1]. On the other hand, other codes use an approximate form of eq. 1, where the advective term is replaced by another diffusion coefficient, making this equation fully diffusive: MESA (Paxton et al., 2013), STERN (Petrovic et al., 2005), or Kepler (Heger et al., 2005). There is so far no consensus about which implementation should be used. However, the reader should keep in mind that both implementations provide different results in terms of evolution of the surface velocities and chemical species (Ekström et al., 2012; Georgy et al., 2013; Brott et al., 2011; Chieffi & Limongi, 2013; Martins & Palacios, 2013).

Another caution is linked to the uncertainty of the choice of the vertical or horizontal diffusion coefficients. Different choices can also lead to qualitatively different results (Meynet et al., 2013).

3.4 Effects of rotation on stellar evolution

Surface abundances. One of the most important effect of rotation is the modification of the surface chemical composition as a function of time, due to the rotation-induced internal mixing. For most of massive star models, it implies that chemical species produced in the core of the star during hydrogen-burning are progressively brought to the surface. For example, it implies an increase of the N abundance, while

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[1]This list is indicative only and has no ambition to be complete. It mostly covers the codes used in the massive star community.

C and O abundances decrease. This effect is generally stronger for higher mass star and at lower metallicity (Ekström et al., 2012; Georgy et al., 2013). In the most extreme cases, internal mixing favours the evolution towards the Wolf-Rayet stage, making it occur earlier in the lifetime of a massive star, or for lower initial mass stars (e.g. Georgy et al., 2012).

Tracks in the HRD. On the Zero-Age Main-Sequence, a rotating model is cooler and less luminous than its non-rotating counterpart. This is due to the support of the centrifugal acceleration, making the model behaves as a lower mass one. After the ZAMS, internal mixing brings fresh hydrogen into the core, making its mass diminish more slowly, and thus keeping the star at higher luminosity. At the same time, the change in the surface abundances (more helium, less hydrogen) makes the star evolve at higher effective temperature than in the non-rotating case (Meynet & Maeder, 2000). In some extreme cases, for very rapidly rotating star, the mixing is so efficient that the star can evolve nearly homogeneously (Yoon & Langer, 2005; Meynet & Maeder, 2007; Szécsi et al., 2015).

Lifetimes. Due to the ingestion of fresh hydrogen by the core during the MS due to rotational mixing, the lifetime of the star are increased (Georgy et al., 2013). The increase of the lifetime can reach several tens of percent with respect to the non-rotating case. This has consequence on the computation of isochrones (Georgy et al., 2014b).

4 Conclusions

In this paper, we have briefly discussed the implementation of convection and rotation in stellar evolution codes, in particular in the context of massive star evolution. Current implementations of convection are described, and we highlight the shortcomings shown by recent multi-dimensional hydrodynamics simulations or observations. The various ways of dealing with rotation are also explained. Finally, we discussed some impacts of the inclusion of rotation on our understanding of stellar evolution.

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