Effects of Rotation on Presupernovae Models

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Abstract. We show that rotation strongly affects the nature of the supernova progenitor (blue/red supergiant or Wolf–Rayet star), and thus the supernova types. In particular our models well reproduce the variations of the number ratio SNIb/Ic to SNII with metallicity. Rotation also produces envelope enrichments of the N/C ratio, and increases the size of the CO cores. We show the evolution of the specific angular momentum up to the preSN stage and make comparison with neutron stars. We suggest that the rare WO stars, preferentially formed at low metallicity, are the progenitors of GRB.

1. Some observational tests of the stellar models

Models taking account of the effects of rotation for massive stars can reproduce the observed surface enrichments (Heger & Langer 2000; Meynet & Maeder 2000), they can explain the great number of red supergiants observed in the SMC (Maeder & Meynet 2001). In both cases, non–rotating models fail to fit these observed features. Rotation also favours the formation of WR stars (Maeder 1987; Fliegner & Langer 1995; Meynet & Maeder 2003, 2004). Let us recall that for a star to be considered as a WR star, at least two conditions must be fulfilled: first, the star must be in the blue part of the HR diagram (typically log$T_{\text{eff}}$ > 4.0) and secondly, the mass fraction of hydrogen at the surface $X_s$ must be inferior to $\sim 0.4$. In the case of non–rotating models, the decrease of the H–abundance at the surface can only result from the uncovering of the outer layers by stellar winds. In rotating models, it results from the action of both the stellar winds and the rotational mixing. Rotation thus adds its effects to that of mass loss and makes easier the entry into the WR phase. Numerical models show that, for a given initial mass and metallicity, rotation increases the WR lifetime with respect to the values obtained by non–rotating models. It also lowers the minimum initial mass of single stars going through a WR phase. In that respect, rotation has qualitatively similar effects as an enhancement of the mass loss rates.

One can easily estimate the theoretical number ratio of WR to O–type stars in a region of constant star formation. This ratio is simply given by the ratio of the averaged lifetimes of a WR star to that of an OV–type star. The averaged lifetimes are weighted means of the lifetimes over the initial mass function (IMF). Assuming a Salpeter IMF slope (d$N$/d$M$ $\propto M^{-(1+\alpha)}$, $x = 1.35$), considering the O–type and WR star lifetimes given in Meynet & Maeder (2004), we obtain the predicted ratios plotted in Fig. 1 (left panel). We assume here that the $v_{\text{ini}} = 300$ km s$^{-1}$ stellar models are well representative of the behaviour of the majority of the OB stars. The values for the non–rotating models are well below the
Figure 1.  

Left: Variation of the number ratios of Wolf–Rayet stars to O–type stars as a function of the metallicity. The observed points are taken as in Maeder & Meynet (1994). The dotted line shows the predictions of the models of Meynet et al (1994) with normal mass loss rates. The continuous and the dashed lines show the predictions of the present rotating and non–rotating stellar models respectively. The black pentagon shows the ratio predicted by Z=0.040 models computed with a metallicity dependence of the mass loss rates during the WR phase. Right: Variation of the number ratios of type Ib/Ic supernovae to type II supernovae. The crosses with the error bars correspond to the values deduced from observations by Prantzos & Boissier (2003). The dotted line is an analytical fit proposed by these authors. The continuous and dashed line show the predictions of the present rotating and non–rotating stellar models.

observed values. The ratios predicted by the models with rotation are in much better agreement with the observations.

What do such models, which successfully fit many observed properties of massive stars, predict for the presupernovae stage and thus for the initial conditions of the supernovae explosions? This is the question addressed in the next sections.

2. Nature of the supernova progenitors

Depending on rotation, a given initial mass star may end its life as a red, a blue supergiant or as a Wolf–Rayet star. Let us first consider this latter case. Current wisdom associates the supernovae of type Ib/Ic with the explosion of WR stars, the H–rich envelope of which has been completely removed either by stellar winds or by mass transfer through Roche Lobe overflow in a close binary system. For single star models at least, theory predicts that the fraction of type Ib/Ic supernovae with respect to type II supernovae should be higher at higher metallicity. The reason is the same as the one invoked to explain the increasing number ratio of WR to O–type stars with the metallicity, Z, namely the growth of the mass loss rates with Z. Prantzos & Boissier (2003) have derived from published data the observed number ratios of type Ib/Ic supernovae to type
Figure 2. Left: Evolution of the $T_{\text{eff}}$ as a function of the fraction of the lifetime spent in the He–burning phase for 20 $M_\odot$ stars with different initial velocities. Right: HR–diagram for 20 $M_\odot$ models at solar metallicity: solid, dashed, dotted-dashed and dotted lines correspond respectively to $v_{\text{ini}} = 0, 100, 200$ and 300 km s$^{-1}$.

II supernovae for different metallicities. The regions considered are regions of constant star formation rate. Their results are plotted in the right panel of Fig. 1. One sees that rotating models give a much better fit to the observed data than non–rotating ones. This comparison can be viewed as a check of the lower initial mass limit $M_{\text{WNE}}$ of the stars evolving into a WR phase without hydrogen. The comparison between the observed and predicted number ratio of WR to O–type stars shown in the left panel of Fig. 1 involves not only the value of the minimum initial mass of stars evolving into the WR phase but also the durations of the WR phase. In that respect the comparison with the supernovae ratios is a more direct check of the correctness of the value of $M_{\text{WNE}}$ which at high metallicity appears rather close to $M_{\text{WR}}$.

Rotation also affects the colour of the supergiants. In Fig. 2 (left), the evolution of $\log T_{\text{eff}}$ as a function of time during the core He–burning phase is shown. One sees that at $Z = 0.004$, non–rotating models spend nearly the whole He–burning phase in the blue part of the HR diagram, while, when rotation increases, the time spent in the red increases at the expense of the time spent in the blue. The physical reason for this behaviour is given in Maeder & Meynet (2001) and is related to the mixing induced by rotation. Interestingly, as briefly mentioned in Sect. 1, observation shows a great number of red supergiant in the Small Magellanic Cloud, a fact which may be easily reproduced by rotating models but which is in contradiction with the predictions of the non–rotating ones.

Figure 2 (right panel) illustrates this same behaviour for different 20 $M_\odot$ models at solar metallicity. For $v_{\text{ini}} \leq 100$, the stellar models would explode when the star is a red supergiant. For higher initial velocities, the supernova progenitor would be a blue supergiant or even a WR star. Not only the colours of the supergiants depend on rotation but also their structure and their chemical composition (Heger et al. 2000; Hirschi et al. 2004). For instance the mass of
the CO core in the $v_{\text{ini}} = 300$ km s$^{-1}$ model is $5.86 \ M_\odot$, which is about 1.5 times the mass of the corresponding core in the non-rotating model. Also the N/C ratio at the surface of the non-rotating model at the presupernova stage is equal to 3.4 (in number). At the surface of the rotating models the N/C ratios are equal to 8.2, 40.2 and 76.0 for $v_{\text{ini}} = 100$, 200 and 300 km s$^{-1}$ respectively. These differences will modify the supernova explosion, the chemical composition of the ejecta and may change the nature of the stellar remnant at least for those stars which are at the limit between those producing neutron stars and those giving birth to black holes.

3. Angular momentum at the pre-supernova stage and the progenitors of GRBs

Meridional circulation, shear instabilities, convection, radial movements, mass loss at the surface, all these processes affect the distribution of the angular velocity in the stellar interior and therefore the distribution of the angular momentum. For the most massive stars, the evolution of the total angular momentum is dominated by mass loss. Typically for the 60 $M_\odot$ model with $v_{\text{ini}} = 300$ km s$^{-1}$, the total angular momentum decreases by a factor 6 during the O-type star phase and by a factor 17 during the WR phase. This star looses more than 99% of its initial angular momentum, between the ZAMS and the end of the core He–burning phase. For the 120 $M_\odot$, the quantity of angular momentum lost amounts to 99.96% of its initial value. When the initial mass decreases, mass...
loss rates become weaker and thus the quantities of angular momentum lost are smaller.

More interesting is how the angular momentum of the core of the star is evolving as a function of time. The angular momentum of the core depends on the transport processes active during the whole evolution of the star. Among the three transport processes considered, convection, shear diffusion and meridional circulation, the first two always transport angular momentum inside-out, only meridional circulation can, in some circumstances, transport angular momentum from the outer parts of the star into its inner parts. In Fig. 3 (left panel) the specific angular momentum of the central region of the star is shown for various initial masses at solar metallicity and for three evolutionary stages: the ZAMS, the beginning of the WR phase for the most massive stellar models, and the end of the core He–burning phase. By central region of the star, we mean here the part of the star which at the end will remain locked in the stellar remnant (either under the form of a black hole or a neutron star\(^1\)). One sees that the angular momentum of the core decreases as a function of time, clearly showing that the outwards transport processes dominate over the inwards ones. The most important decrease occurs during the core H–burning phase.

The right panel of Fig. 3 compares the specific angular momentum of neutron star to that at the end of the core He–burning phase. At this stage, the specific angular momenta of the central regions have nearly reached their final values (see the contribution by Hirschi in the present volume). We see that angular momentum contained in the core is much higher than the one contained in young pulsars. This important excess of angular momentum might be evacuated either during the pre-supernova evolution by mechanisms not accounted for in the present models (for instance the effects of a magnetic field have been explored by Woosley & Heger [2004] and Maeder & Meynet [2004]), or at the time of the supernova explosion, or at the beginning of the neutron star life. On the other hand, the specific angular momentum obtained is sufficiently high for generating a GRB through the collapsar model (Woosley [1993]). A high angular momentum is likely not the only condition however for producing a GRB, the star should form a black hole and should likely have lost its H–rich envelope.

The association of GRB with hypernovae of the class of SNIc is supported by several observations (e.g. see Mazzali et al. [2003]). SNIc result from the explosion of a star without H and with little or no He. This corresponds to a rare category of WR stars: the so-called WO stars. These stars show the products of He-burning, with an excess of C+O with respect to He and O > C. They result from the evolution of stars with \( M \geq 60 \, M_\odot \) at low metallicity only (Smith & Maeder [1991]). Why only at low metallicity? The reason is the following: at high \( Z \), mass loss is high, thus when the products of the 3\( \alpha \) reaction appear at the surface, they are in an early stage of nuclear processing, i.e. with a low \((\text{C+O})/\text{He}\) ratio. At low \( Z \), because the stellar winds are weaker, the products of the 3\( \alpha \) reaction rarely appear at the stellar surface and if they do it (e.g. in case of high rotation) this occurs very late in the evolution, i.e. when \((\text{C+O})/\text{He}\) is high and the star is an early WC star or a WO star. Such a scenario is confirmed by the observation which shows that early WC types and

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WO stars are only found in lower $Z$ regions \cite{Smith_Maeder_1991}. At solar metallicity, the present stellar models predict no WO stars to be formed. At $Z = 0.004$, only stars in the mass range between $\sim 50$–70 $M_\odot$ become WO stars. This would mean that at this metallicity, about 2% of the core collapse supernovae would produce a GRB, a value not too far from the estimate deduced from the observed frequency of GRB \cite{Woosley_Heger_2004}.

4. Conclusion

The inclusion of rotation in stellar models improve the agreement with the observations. The stellar type of the progenitors of the supernovae, the chemical composition of the ejecta and the nature of the remnant depend on rotation. The quantity of angular momentum in the central region at the time of the explosion has an impact on the observed characteristics of the explosion. Even for stars losing mass at a high rate, the specific angular momentum of the core is largely sufficient for producing a collapsar. A GRB, however will only appear when special conditions are met, realised only in a small fraction of core collapse supernovae. Let us add also that rotation modifies the way massive stars lose mass. It induces anisotropy \cite{Maeder_1999} and enhances the mass loss rates \cite{Maeder_Meynet_2000}. This may change the conditions in the surroundings of the star and therefore the interactions of the supernova ejecta with the circumstellar material.

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Figure 3. **Left**: Specific angular momentum in the central regions (see text) on the ZAMS, at the entrance into the WR phase, and at the end of the core He–burning phase. **Right**: Specific angular momentum in the central regions at the end of the core He–burning phase, for neutron stars rotating at the break–up limit and for young pulsars. For the momentum of inertia of the neutron star we used the relation \( I_{\text{NS}} = 0.32 M R^2 \) as in Heger (1998), where \( M \) is taken equal to \( M_{\text{rem}} \) and \( R \) is given by the relation \( R/R_\odot = 15.2/ (M/M_\odot)^{1/3} \) derived from the theory of polytropes.

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