The evolution of massive stars in the context of V838 Monocerotis

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Abstract. The aim of this paper is to look at the evolution of massive stars in order to determine whether or not the progenitor of V838 Mon may be a massive star. In the first part of this paper, the evolution of massive stars around solar metallicity is described, especially the evolution in the Hertzsprung-Russell (HR) diagram. Then, using the observational constraints, the probable progenitors (and their evolution) are described. Using models of single stars, no progenitor can be found amongst massive stars that can satisfy all the observational constraints. Wolf-Rayet stars (stars with initial masses above about 30 $M_\odot$, which have lost their hydrogen rich envelopes) could explain 10 to 100 $M_\odot$ of circumstellar material but they are very luminous ($L \gtrsim 10^5 L_\odot$). Main sequence stars crossing the HR diagram and becoming red supergiants (RSG) can have very low effective temperatures but take thousands of years to cross over. Be stars (fast rotating stars with a mass around 10 $M_\odot$), which form disk or B stars accreting matter from a binary companion of a similar mass would need to be compared in detail with the observational constraints. In the future, there will hopefully be further observational constraints on the models coming from the mass and nature (interstellar or circumstellar) of the material producing the light echo and from a frequency estimate of spectacular objects such as V838 Mon.

1. Introduction

V838 Monocerotis is a peculiar object, which had a major outburst in February 2002 [Kimeswenger et al. 2002]. Its V magnitude first rose to 10th magnitude early in January. Then it rose to a peak magnitude of 6.5 around February 2nd. Afterward it had two secondary peaks to magnitudes 7 and 7.5 in March and April respectively. Finally a decline brought the V magnitude down to 15 by mid-May 2002. Note that V838 became (peak around 4 or 5th magnitude) and stayed brighter in redder bands (for example the J and K bands). This means that the star after the eruption became a very cool star ($T_{\text{eff}} \lesssim 2000$ K, see contribution by Martin in this volume). Similar objects are M31 RV and V4332 Sgr (Kimeswenger in this volume). Apart from its outbursts, V838 Mon is famous for the light echoes observed with Hubble Space Telescope (Bond in this volume). Indeed light emitted during the bursts is scattered by the surrounding material towards us with a delay. At a given time, we receive light from an ellipsoidal surface of the circumstellar material (Sugerman in this volume). Ashok (in this volume) with Spitzer observations of dust thermal re-radiation estimates the amount of circumstellar material to be between 10 and 100 $M_\odot$. It is however not known yet whether this material is of interstellar origin.
or of circumstellar origin (lost by V838 progenitor). SiO maser emission was also detected in V838 Mon 3 years after its outburst (Deguchi in this volume). There are several additional observational constraints concerning V838 and its progenitor. The latest distance estimate using polarimetry of the light echo is around 6 kpc (Sparks in this volume). The metallicity of V838 is [Fe/H] = $-0.4 \pm 0.3$ (Kipper et al. 2004) corresponding approximately to the metallicity of the Large Magellanic Cloud (LMC: $Z \sim 0.008$). Most elements are in solar ratio compared to iron and the chemical composition is compatible with unprocessed material at the galacto-centric distance of V838. V838 has a B3V companion and a spectroscopic fit for the progenitor of V838 is obtained with a star with a high effective temperature ($T \sim 50,000$ K) and with $V \sim 15.5$ and $B - V \sim 0.5$ (Munari et al. 2005). Tylenda & Soker (2006) estimate the progenitor luminosity to be around $1000 L_\odot$ and the maximum luminosity during outburst to be around $10^6 L_\odot$ (using a distance of 8 kpc). Several models have been proposed for the progenitor of V838: a born-again low mass star (Lawlor 2005), a WR star (Munari et al. 2005), a planet swallowing star (Retter et al. 2006) and a binary star merger (Tylenda & Soker 2006).

2. Stellar evolution models

The computer model used to calculate the results presented here is described in Meynet & Maeder (2005, 2003). Convective stability is determined by the Schwarzschild criterion. Overshooting is included with an overshooting parameter of 0.1 $H_p$ for H and He–burning cores and 0 otherwise, where $H_p$ is the pressure scale height estimated at the Schwarzschild boundary. The reaction rates are taken from the NACRE (Angulo et al. 1999) compilation. The effective temperature of Wolf–Rayet (WR) stars is a delicate problem, since the winds may have a non–negligible optical thickness. A correction has been applied in the WR stages and only there (see Meynet & Maeder 2005, for more details).

There are three kinds of effects induced by rotation. First, the centrifugal force acts again gravity and elongates isobars at the equator. Second, rotation enhances mass loss. Third, it induces mixing in radiative zones. Instabilities induced by rotation taken into account are meridional circulation and secular shears. They affect both the transport of the chemical species and of the angular momentum (Maeder & Meynet 2000b). Since mass loss rates are a key ingredient of the models for massive stars, let us recall the prescriptions used. The changes of the mass loss rates, $\dot{M}$, with rotation are taken into account as explained in Maeder & Meynet (2000a). As reference mass loss rates, the adopted mass loss rates are the ones of Vink et al. (2000, 2001), who account for the occurrence of bi–stability limits, which change the wind properties and mass loss rates. For the domain not covered by these authors the empirical law devised by de Jager et al. (1988) was used. Note that this empirical law, which presents a discontinuity in the mass flux near the Humphreys–Davidson limit, implicitly accounts for the mass loss rates of LBV stars. For the non–rotating models, since the empirical values for the mass loss rates are based on stars covering the whole range of rotational velocities, one must apply a reduction factor to the empirical rates to make them correspond to the non–rotating case. Here, the same reduction factor was used as
in [Maeder & Meynet (2001)]. During the Wolf–Rayet phase the mass loss rates by Nugis & Lamers (2000) were used. The mass loss rates during the non–WR phases depend on metallicity as $\dot{M} \sim (Z/Z_\odot)^{0.5}$ [Vink et al. 2001], where $Z$ is the mass fraction of heavy elements at the surface of the star.

Models were calculated at four different metallicities: $Z = 0.004$, $0.008$, $0.020$ and $0.040$ [Meynet & Maeder 2003, 2005]. The initial compositions are adapted for the different metallicities considered here. For the heavy elements, the same mixture as the one used to compute the opacity tables for solar composition (Iglesias & Rogers 1996) was adopted. The models have the following initial mass fractions for hydrogen $X = 0.757$, $0.744$, $0.705$ and $0.640$ and for helium $Y = 0.239$, $0.248$, $0.275$ and $0.320$ at the metallicities $Z = 0.004$, $0.008$, $0.020$ and $0.040$ respectively.

As initial rotation, a value equal to 300 km s$^{-1}$ is considered on the zero age main sequence (ZAMS) for all the initial masses and metallicities considered. At solar metallicity, this initial value produces time–averaged equatorial velocities on the main sequence (MS) well in the observed range, i.e. between 200 and 250 km s$^{-1}$. At low metallicities this initial rotational velocity corresponds also to mean values between 200 and 250 km s$^{-1}$ on the MS phase, while at twice the solar metallicity, the mean velocity is lower, between 160 and 230 km s$^{-1}$. Presently we do not know the distribution of the rotational velocities at these non–solar metallicities and thus we do not know if the adopted initial velocity corresponds to the average observed values. It may be that at lower metallicities the initial velocity distribution contains a larger number of high initial velocities [Maeder et al. 1999], in which case the effects of rotation described below would be underestimated at low metallicity.

3. Evolution of massive stars with rotation and mass loss

3.1. Impact of rotation

The main impacts of rotation on the evolution are the following. Rotation increases the MS lifetime with respect to non-rotating models (up to about 40 %). Rotation strongly affects the lifetimes as blue and red supergiants (RSG). In particular in the SMC, the high observed number of RSG can only be accounted for by rotating models [Maeder & Meynet 2001]. Rotation increases mass loss and therefore the minimum mass for forming WR stars is lowered from 37 to 22 $M_\odot$ for typical rotation at solar metallicity. Rotation also increases the WR lifetimes (on the average by a factor two). The observed variation with metallicity of the fractions of type Ib/Ic supernovae with respect to type II supernovae (or in other words of WR to O type stars) as found by Prantzos & Boissier (2003) is very well reproduced by the rotating models, while non–rotating models predict much too low ratios.

The effects of rotation on pre–supernova models are significant between 15 and 30 $M_\odot$ [Hirschi et al. 2004]. Indeed, rotation increases the core sizes (and the yields of carbon and oxygen) by a factor $\sim 1.5$. Above 20 $M_\odot$, rotation may change the radius or colour of the supernova progenitors (blue instead of red supergiant) and the supernova type (IIb or Ib instead of II). Rotation affects the lower mass limits for radiative core carbon burning, for iron core collapse
Figure 1. Final mass of the rotating stellar models as a function of the initial mass at the four metallicities $Z = 0.004, 0.008, 0.020$ and $0.040$ (from top to bottom). The line with slope one, labeled $\dot{M} = 0$, corresponding to the case without mass loss, shows how important mass loss is for stars more massive than about $25 \, M_\odot$ (Meynet & Maeder 2005).

and for black hole formation. Finally, rotating models are able to reproduce surface enrichments during the main sequence (in particular in nitrogen) whereas non–rotating models predict surface enrichments only after the first dredge–up (Meynet & Maeder 2000; Heger & Langer 2000).

3.2. Mass loss

Mass loss increases with metallicity (dependence on $Z^{1/2}$ in our models) and stellar mass (or luminosity). This of course has a direct impact on the final mass of the models, which is shown in Fig. 1. In this figure, we can see that more metal rich models end up with smaller final masses. Note however that models with an initial mass around $100 \, M_\odot$ all end up with a similar final mass and they all lose about $90 \, M_\odot$ during hydrogen and helium burnings. The minimum mass to form a WR star is estimated at 20, 22, 25 and 32 $M_\odot$ for metallicities $Z = 0.004, 0.008, 0.020$ and 0.040 respectively.
Figure 2. Evolution of the $Z = 0.020$ models in the HR diagram (Meynet & Maeder 2003).
3.3. Evolution in the Hertzsprung-Russell diagram

The evolution of solar metallicity models ($Z = 0.020$) in the HR diagram is shown in Fig. 2. The massive star range can be divided in the following bins:

- $M \lesssim 13 M_\odot$: the star becomes a red supergiant (RSG) after the main sequence (MS) and undergoes a blue loop before ending up as a RSG. Stars less massive than about 10 $M_\odot$ will go through the AGB phase (not followed in this work).

- $M \simeq 13 - 20 M_\odot$: the star crosses only once the HR diagram after the MS and ends as a RSG.

- $M \simeq 20 - 40 M_\odot$: the star becomes a RSG and loses its hydrogen rich envelope due to mass loss and then becomes a Wolf–Rayet (WR) star.

- $M \gtrsim 40 M_\odot$: the star becomes a Wolf–Rayet (WR) star and never goes through the RSG stage although it might go through the luminous blue variable (LBV) stage.

4. Comparison between observations and models

Kipper et al. (2004) find a metallicity $[\text{Fe/H}] = -0.4 \pm 0.3$ for V838 Mon. V838 Mon therefore has a sub-solar metallicity close to that of the Large Magellanic Cloud (LMC: $Z \sim 0.008$). The lower bound for metallicity is close to that of the Small Magellanic Cloud (SMC: $Z \sim 0.004$ or $[\text{Fe/H}] \sim 0.7$). We therefore concentrate on LMC ($Z=0.008$) metallicity models to find a progenitor, while solar ($Z=0.020$) and SMC ($Z=0.004$) metallicity models are representative for
models at the upper and lower bounds of the metallicity determination for V838 Mon.

How does the evolution in the HR diagram changes between solar and LMC metallicities? The opacities being lower, the models are a bit bluer and hotter during the main sequence. The main difference comes however from mass loss. This means that the models below $20 \, M_\odot$ are not significantly different between solar and LMC metallicities. The evolution of the sub-solar metallicity models in the HR diagram is shown in Fig. 3 for models more massive than $20 \, M_\odot$. The minimum initial mass model, which forms a WR star increases to $25 \, M_\odot$ at $Z_{\text{LMC}}$ (and $32 \, M_\odot$ at $Z_{\text{SMC}}$). The minimum mass model to evolve directly to the WR stage without going through the RSG stage increases as well. For example, the $60 \, M_\odot$ models at $Z_{\text{LMC}}$ (and $Z_{\text{SMC}}$) do go through the RSG stage. Therefore the lifetime in the WR stage decreases with metallicity. and, as said earlier (except for the very massive models with $M \sim 100 \, M_\odot$), the final mass is higher at lower metallicity.

Can a WR star be the progenitor of V838 Mon? WR models have effective temperatures between 50 000 and 25 000 K compatible with observations. The most massive ones can lose up to $100 \, M_\odot$ during their lifetime corresponding to the amount of circumstellar material determined by Ashok. On the other hand, they are very luminous $L \gtrsim 10^5 \, L_\odot$ and it seems hard to reconcile it with a $V = 15$ and $B-V = 0.5$ progenitor at 6 kpc. WR are also unlikely to evolve to the RSG. Using models at $Z_{\text{SMC}}$ does not help the comparison with the observations of V838 Mon progenitor.

What other possibilities are there? A main sequence single star with an initial mass around $18 \, M_\odot$ is not a probable progenitor because it is still very luminous and because the time it takes to cross the HR diagram to the RSG stage is thousands of years. One advantage is nevertheless that the such a RSG reaches very low effective temperatures, around 3500 K, which is required by present observations. V838 Mon companion is a B3V star and the progenitor star was not so different from the companion (Munari et al. 2005). It is therefore possible that the progenitor was also a main sequence B star (Tylenda & Soker 2000). The 2002 event cannot be due to the usual crossing of the HR diagram at the end of the main sequence because a normal star takes too much time to become a RSG and its luminosity does not change drastically before or during the crossing. Can it be related to the Be phenomenon (B star with a disk)? Is it due to a mass transfer from a similar mass companion? These pathways have not been explored yet, so it is difficult to say whether they could reproduce the observations or not. The other progenitor models are: a merger (Tylenda & Soker 2006), a star capturing its planets (Retter et al. 2006) and a born-again low mass star (Lawlor 2005). The references given for each model discuss in detail their advantages and negative points. It would be very interesting to estimate frequencies of the different models as well as the frequency of objects like V838 Mon (including or not M31 RV and V4332 Sgr) and to compare them to gain additional constraints.

5. Conclusion

The evolution of stellar models for massive rotating stars including mass loss was presented with an emphasis on the evolution in the Hertzsprung–Russell
diagram. In particular, models of WR stars and of single massive stars were compared to the observations of the V838 Mon. Even though there is no simple evolutionary scenario able to explain V838 Mon eruption, it is interesting to note a few similarities. WR stars, although too luminous, are able to lose up to 100 $M_\odot$ of material during their lifetime. Massive stars reach lower RSG effective temperatures, down to 3500 K.

The usual crossing of the HR diagram by a single star after the main sequence cannot explain the 2002 eruption due to timescale and luminosity problems. The influence of accretion from a binary companion or disk formation should be investigated. Additional constraints can be put on the progenitor models by determining the origin (interstellar or circumstellar) and the mass of the material producing the light echoes and by estimating the frequency of objects like V838 Mon.

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