The evolution of massive stars: a selection of facts and questions

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Abstract.
In the present paper we discuss a selection of facts and questions related to observations and evolutionary calculations of massive single stars and massive stars in interacting binaries. We focus on the surface chemical abundances, the role of stellar winds, the early Be-stars, the high mass X-ray binaries, the effects of rotation on stellar evolution. Finally, we present an unconventionally formed object scenario (UFO-scenario) of WR binaries in dense stellar environments.

1. Introduction

The overall evolution of massive stars is critically affected by uncertainties in various physical processes which determine the stellar structure. To illustrate, we do not know whether semi-convection is slow or fast, whether convective core overshooting is small or large. There is no unanimousness about the effects of rotation on stellar evolution (see also section 6). It is a fact however that for the most massive stars stellar wind mass loss is important in order to understand their evolution (section 3). Moreover, the evolution of massive close binaries is determined by processes which are a fact but where the physics is in some cases only a best guess. We distinguish stable Roche lobe overflow (RLOF) (where the behaviour of the mass loser is well understood) accompanied by the mass transfer (conservative or non-conservative this is the question), mass accretion (always accompanied by momentum accretion causing a spin-up of the mass gainer), common envelope evolution (very non-conservative: fact), the supernova (SN) explosion of one of the binary components (the SN is in many cases asymmetrical: fact) which disrupts many systems (fact), the spiral-in process of binaries with extreme mass ratio (some massive binaries survive this process, survive two SNs and form a binary pulsar: fact), the merger process of the two components. Due to the limited space it is unfeasible to discuss the facts and questions of these processes in detail. A more extensive description was given in Vanbeveren et al. (1998a). In the present paper I prefer to propose facts and questions related to a personal selection of observations of massive stars.

2. The surface chemistry of massive stars

The surface layers of many OB supergiants and of some OB-dwarfs are nitrogen enriched (fact). Five processes may be responsible: rotational mixing combined
with stellar wind mass loss, the RLOF process in interacting binaries where the surface layers of the mass loser but also of the mass gainer may becomes N-enriched, the merger of two binary components due to a highly non-conservative RLOF (common envelope phase) and last not least, the collision and merger process due to N-body dynamics in young dense stellar systems.

Question: if RLOF has played an important role during the progenitor evolution of WR+OB binaries and of high mass X-ray binaries (HMXBs), we may expect that the OB companions in these systems are N-enriched. Has this been observed, in some or in a majority of systems?

3. The stellar wind mass loss rates

The stellar wind mass loss rates during the core hydrogen burning (CHB) phase before the star eventually becomes a luminous blue variable (LBV) has been the subject of detailed research during the last 3 decades. Here we focus on the LBV phase, the red supergiant (RSG) phase and the Wolf-Rayet (WR) phase during core helium burning (CHeB).

Hydrodynamic simulations (within its limitations) let us suspect that rotating stars (even those with moderate rotational velocities) with a luminosity close enough to the Eddington value, will lose mass at very high rate (Aerts et al., 2004 and references therein). LBVs are stars with \( \gamma = L/L_{Edd} \) close to 1. One of the most famous LBVs is \( \eta \) Car, a star with \( \gamma > 0.7 \) and an observed average mass loss rate \( \sim 10^{-3} \, M_\odot/yr \) (high + low state). Observations reveal that \( \eta \) Car type LBVs are hydrogen burning stars with a luminosity larger than the maximum luminosity of RSGs. The interpretation could be the following: LBV-type mass loss is large enough in order to prevent a star to expand and to become a RSG and detailed evolutionary calculations show that a rate \( \sim 10^{-3} \, M_\odot/yr \) is indeed sufficient in order to prevent the redward evolution of a star with an initial mass \( \geq 40 \, M_\odot \). The consequence for binaries is then obvious: RLOF does not happen (or its importance is significantly reduced) in case B/C and late case A binaries with primary mass larger than 40-50 \( M_\odot \) (the LBV scenario of very massive stars as it was introduced in Vanbeveren, 1991). This LBV-type instability may be the reason why no or very few stars are observed with a luminosity (with corresponding mass) larger than the luminosity of a 100-120 \( M_\odot \) evolutionary track (an exception may be the Pistol Star, Figer et al., 1998). Evolutionary calculations reveal that already on the zero age main sequence, a 150 \( M_\odot \) has a \( \gamma = 0.9 \), a 200 \( M_\odot \) even has \( \gamma = 0.96 \). This let us suspect that rotating stars with an initial mass \( > 120 \, M_\odot \) may suffer from a very high stellar wind mass loss rate already at zero age. The consequences are obvious: when a star is formed with a mass \( > 120 \, M_\odot \), it will very soon evolve into a state where it is almost undistinguishable from a star whose mass was \( \sim 120 \, M_\odot \) on the zero age main sequence.

Notice that the process discussed above also affects in a critical way the outcome of N-body dynamical computations of young dense stellar systems, and in particular the formation of intermediate mass black holes (IMBH) by runaway collision (Portegies Zwart et al., 2004). Simulations performed by Belkus et al.
(2005, see also the present proceedings) reveal that due to the action of an LBV type instability in stars with a mass $> 120 \, M_\odot$ formed by stellar collisions (remark that a collision implies spinning up of the merger and this amplifies the LBV type instability and mass loss rate), the formation of an IMBH by runaway collision in young dense stellar systems is less likely.

Our RSG stellar wind mass loss knowledge was and is still very bad. The effect on stellar evolution has been investigated by the Geneva group using a formalism proposed by de Jager et al. (1988), by the Brussels group using a formalism proposed by Vanbeveren et al. (1998a, b) and by the Padua group using a formalism presented by Salasnich et al. (1999) which is quite similar to the one of Vanbeveren et al. These 3 formalisms have been critically discussed by Crowther (2001). Notice that the main evolutionary difference between the Geneva treatment and the Brussels-Padua one concerns stars with an initial mass $\leq 25-30 \, M_\odot$. When the RSG wind formalism proposed by the Brussels-Padua group is implemented into a stellar evolutionary code, it follows that all galactic single stars with a mass between $\sim 20 \, M_\odot$ and the LBV-mass limit of 40-50 $M_\odot$ quoted above lose most of their hydrogen rich layers during the RSG phase and become WR stars. The consequence for binaries: RLOF and thus common envelope evolution does not happen in case C binaries with primary mass larger than $\sim 20 \, M_\odot$ (the RSG scenario as it was introduced in Vanbeveren, 1996). Even more: using the RSG formalism also for stars with initial mass $\leq 20 \, M_\odot$, it follows that stars with a mass as small as 10 $M_\odot$ may lose a significant amount of hydrogen rich layers (but not all) by RSG wind. Remark that Vanbeveren et al. (1998) proposed a model for the binary $\upsilon$ Sgr where the effect of the RSG wind is essential. Even more, it was concluded that without this RSG wind it is impossible to explain the system.

The masses of black hole (BH) remnants of stars with initial mass $\leq 120 \, M_\odot$ predicted by stellar evolutionary computations depend on the effect of stellar wind mass loss on massive star evolution, and more specifically on the mass loss during the CHeB-WR-phase. Before 1998, most of the massive star evolutionary calculations used a WR-mass loss rate formalism which was based on theoretical interpretation of WR spectra with atmosphere models that assume homogeneity of the stellar wind (Hamann, 1994). However, two years later, Moffat (1996) and Hillier (1996) presented evidence that WR winds are inhomogeneous implying that the real WR mass loss rates were smaller by at least a factor 2-3. In 1998, we were among the first to perform and publish evolutionary computations of massive stars with such reduced WR mass loss rates (Vanbeveren et al., 1998a, b, c). At that time, the evolutionary-referees were not always in favor, to express it mildly. After 1998, observational evidence was growing that indeed WR winds are inhomogeneous and that the rates are lower. Since 2000, everybody is using reduced WR-rates in their evolutionary code (probably also our 1998-referees). A major consequence of lower WR mass loss rates is of course the final stellar mass before core collapse. In our 1998 calculations, stars with a metallicity $Z = 0.02$ and with an initial mass $\leq 120 \, M_\odot$ end their life with a mass $\leq 20 \, M_\odot$. When the WR stellar wind mass loss rate is metallicity dependent (as predicted by the radiation driven wind theory, Pauldrach et al., 1994 among many others), the pre-core collapse mass may be as large as 40-50 $M_\odot$ in small $Z$ environments (like the SMC for example).
4. Observations of massive close binaries (facts)

We obviously have the numerous observations of individual massive systems, mainly in the Solar Neighborhood which can learn us a lot about the overall evolution of massive stars. Many of these have been discussed in Vanbeveren et al. (1998).

Less than 50% of the WR stars in the Galaxy and the Magellanic Clouds seem to have an OB type companion (Foelmi et al., 2003); the massive O-type binary frequency in open clusters in the Solar Neighborhood ranges between 14% (Trumpler 14) and 80% (IC 1805) (Mermilliod, 2001); on average 33% of the O-type and early B-type stars in the Solar Neighborhood are primary of a binary with mass ratio secondary mass/primary mass $q > 0.2$ and orbital period $P < 100$ days (Garmany et al., 1980; Vanbeveren et al., 1998a). But accounting for statistical bias, the real massive close binary frequency may be significantly larger (Halbwachs, 1987; Hogeveen, 1991; Mason et al., 2001; Van Rensbergen, 2001).

5. The massive star population

A massive star population is a mixture of unevolved binaries (no interaction yet), evolved binaries (interaction happened), single stars born as single, single stars who became single due to binary evolution (disrupted binaries and mergers). In the case of clusters the population may also be significantly affected by close encounter stellar dynamics. All this means that the binary frequency on the zero age main sequence may be significantly larger than the observed binary frequency in a population. Accounting for the observed OB-type binary frequency discussed in the previous section, it can be concluded that theoretical population predictions which do not account for the effects of binaries may have an academic value but may be far from reality.

The effects of binaries on the O-type and WR-type star population have been discussed frequently in papers published by our group (for a review, see Vanbeveren et al., 1998b). Notice that since 1998, our population prediction of binaries with a compact companion has been updated using the two-component maximum-likelihood kick velocity distribution of Arzoumanian et al., 2002. The new frequencies are higher compared to our 1998 values, but the differences are small enough that they do not change the overall conclusions.

A post-RLOF primary of an interacting binary (that survived the RLOF of course) is always a hydrogen deficient CHeB star. As a consequence, the answers on the following questions affect significantly theoretical population synthesis predictions of WR binaries: what is the minimum mass (luminosity) of a hydrogen deficient CHeB star to show up as a WR star? The WR components in observed WR binaries have a mass $\geq 5-8 \, M_\odot$. If this is a real minimum then it can be expected that, compared to the number of WR+OB binaries, there are many more OB stars with a post-RLOF CHeB companion which does not show up as a WR star.

A minimum mass of hydrogen deficient CHeB stars means a minimum luminosity and it is tempting to translate this into a minimum mass loss rate, i.e.
• what must be the minimum mass loss rate of a hydrogen deficient CHeB star so that this star shows up as a WR star in a binary with an OB-type companion?

• if the mass loss rate is metallicity dependent as predicted by the radiatively driven wind theory, could it be that the minimum mass of a WR star in a binary is larger in the Magellanic Clouds compared to the value holding for the Galaxy?

5.1. The early Be type stars

(Facts) 20% of the Galactic early B-type stars are Be-type. Be-stars are rapid rotators however a significant fraction of the normal early B-type stars have rotational velocities similar to those of the Be-stars (Vanbeveren et al., 1998c) which means that not all rapid rotators are Be stars. There are no Be+B or Be+Be binaries known but many Be stars are binary mass gainers (Be X-ray binaries, φ-Persei types discussed in these proceedings by Douglas Gies).

Question: how many Be stars are binary products i.e. how many Be stars are formed by binary mass exchange or are binary mergers?

To answer this question it may be crucial to remark that some Galactic and Magellanic Cloud clusters contain a large population of Be stars. Six clusters with an age between 19 Myr and 25 Myr, studied by Mermilliod (1981) and by Grebel (1995), have an early Be/B0-B5 number ratio between 0.1 and 0.4. If these fractions can be considered as facts, then the population synthesis study of Van Bever and Vanbeveren (1997) predicts that at most 10-20% of these Be stars can be explained by binary evolution.

5.2. The standard high mass X-ray binaries (HMXBs)

The scenario for the formation of HMXBs proposed by Van den Heuvel and Heise (1972) has been confirmed frequently by detailed binary evolutionary calculations. We distinguish three X-ray phases: 1. the OB star is well inside its critical Roche lobe and loses mass by stellar wind. The X-rays are formed when the compact star accretes mass from the wind (wind fed systems); 2. The OB star is at the beginning of its RLOF phase and mass transfer towards the compact star starts gently (RLOF fed systems); 3. The optical star is a Be star and X-rays are emitted when the compact star orbits inside the disk of the Be star (disk fed systems).

In the massive binary evolutionary simulations performed with the Brussels code, we detected a possible fourth phase: when the OB+compact companion binary survives the RLOF-spiral-in-common envelope phase and the optical star is at the end of its RLOF, burning helium in its core, it transfers mass at a very moderate rate similar as the rate at the beginning of RLOF. The star is overluminous with respect to its mass, the surface layers are nitrogen rich and have a reduced surface hydrogen abundance (X \leq 0.4). Possible candidates with an overluminous optical companion are Cen X-3 and SMC X-1. The question here is how a binary can survive the spiral-in phase? Obviously, some binaries have to survive because we observe double neutron stars. Theoretically the survival probability becomes larger if one accounts in detail for the combined
action of stellar winds and spiral-in. To illustrate, when after the formation of
the compact star, the binary period is large enough so that an LBV-type or
RSG-type stellar wind mass loss can start before the onset of the spiral-in, the
importance of the latter process can be reduced significantly. Our simulations
with the wind rates discussed in section 3 allow to conclude that it cannot be
excluded that some HMXBs are RLOF-fed systems where the optical star is a
core helium burning star at the end of the RLOF/spiral-in.

Most of the supernova type Ib/c happen in binaries and all HMXBs with a
neutron star companion are expected to have experienced (and survived) such a
supernova. Since a WC star is expected to be a type Ic progenitor, evolutionary
calculations predict that the SN shell may contain lots of carbon and oxygen.
When this WC star was a binary component and when the SN shell hits the
OB companion star, quite some C and O may be accreted by the latter and
abundance anomalies may be expected. Performing a detailed analysis of the
CO abundances in the optical star of Cyg X-1 may be interesting. An observed
overabundance may be an indication that the black hole progenitor experienced
a supernova explosion as well, may be even a hypernova.

6. The effect of rotation on massive star evolution

Rotation implies rotational mixing in stellar interiors and it can enhance the
stellar wind mass loss compared to non-rotating stars. This enhancement may
be important for stars that are close to the Eddington limit (LBVs and very
massive stars) and therefore rotation may affect indirectly their evolution.

The observed distribution of rotational velocities has been investigated by
Vanbeveren et al. (1998c) and we illustrated that the majority of the early B-
type stars and of the O-type stars are relatively slow rotators, slow enough to
conclude that rotational mixing only plays a moderate role during their evolution
(the effect is similar to the effect of moderate convective core overshooting). In
the latter paper we argued that due to the process of synchronization in binaries,
accounting for the observed binary period distribution, a majority of primaries
in massive interacting binaries is expected to rotate slow enough so that the
effect of rotation on their overall evolution is moderate as well.

The distribution has an extended tail towards very large rotational veloc-
ities, i.e. the distribution is highly asymmetrical which means that in order to
study the effect of stellar rotation on population synthesis (the WR and the O
type star population for example), it is NOT correct to use a set of evolution-
ary tracks calculated with an average rotational velocity corresponding to the
observed average. This tail obviously demonstrates that there are stars which
are rapid rotators. Binary mass gainers, binary mergers and stellar collision
products in young dense stellar environments are expected to be rapid rotators
and thus are expected to belong to the tail. The question however is whether or
not one can approximate their evolution with rotating single star models.

Due to the dynamo effect, rotation generates magnetic fields (Spruit, 2002)
which means that the evolutionary effect of rotation cannot be studied sepa-
rately from the effects of magnetic fields. This was done only since recently
(Maeder and Meynet, 2004; see also Norbert Langer in the present proceedings)
and (as could be expected) several of the stellar properties (size of the core,
main sequence lifetime, tracks in the HR diagram, surface abundances etc.) are closer to those of models without rotation than with rotation only. Maeder and Meynet argued that since single star evolution with rotation only explains the surface chemistry of the observed massive supergiant population, whereas single star evolution with rotation and magnetic fields does not, magnetic fields must be unimportant. However this argumentation is based on the assumption that most of the massive stars evolve as single stars do. In section 2 I have listed the presently known processes which may be responsible for altered CNO abundances in OB-stars and before an argumentation as the one above has any meaning, one has to consider all these processes.

7. A UFO-scenario for WR+OB binaries

The formation of WR+OB binaries in young dense stellar systems may be quite different from the conventional binary evolutionary scenario as it was proposed by Van den Heuvel and Heise (1972). Mass segregation in dense clusters happens on a timescale of a few million years which is comparable to the evolutionary timescale of a massive star. Within the lifetime of a massive star, close encounters may therefore happen very frequently. When we observe a WR+OB binary in a dense cluster of stars, its progenitor evolution may be very hard to predict. In Brussels we started a project to follow the dynamical evolution of starbursts. The first results are given by Belkus et al. (2005)(see also Belkus et al. in the present proceedings). We combine the N-body integration technique with our detailed population number and spectral synthesis code of starbursts (Van Bever and Vanbeveren, 2000, 2003). Although we are still in the initial phase of this type of research, our simulations predict the following unconventionally formed object scenario (UFO-scenario) of WR+OB binaries. After 4 million years the first WR stars are formed, either single or binary. Due to mass segregation, this happens most likely when the star is in the starburst core. Dynamical interaction with another object becomes probable, especially when the other object is a binary. In our simulations, we encountered a situation where the WR star (a single WC-type with a mass $= 10 \, M_\odot$) encounters a $16 \, M_\odot + 14 \, M_\odot$ circularized binary with a period $P = 6$ days. A possible result of the encounter process is the following: the two binary components merge and the $30 \, M_\odot$ merger forms a binary with the WC star with a period of $\sim 80$ days and an eccentricity $e = 0.3$. This binary resembles very well the WR+OB binary $\gamma^2$-Velorum but it is clear that conventional binary evolution has not played any role in its formation.

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