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The relation between massive A–M supergiants and massive OB type stars, WR stars and sn explosions

ABSTRACT

In this review recent evolutionary computations of massive single stars and of massive close binaries are compared to observations of massive A-M supergiants, massive OB type stars, WR stars and LBVs in order to find relations between these different types. In spite of two discrepancies between the observed HR diagram of OB type stars and tracks of core hydrogen burning stars we conclude that A-M supergiants descend from OB type (mainly) single stars with initial mass between 8 (9) $M_{\odot}$ and 30 $M_{\odot}$. There should be no or only a marginal relation between A-M supergiants and non-evolved close binaries or LBVs whereas less than 10 % of all WR stars within 2.5 kpc from the sun should have had a yellow/red supergiant progenitor. We finally discuss the relation between massive A-M supergiants and different types of SN explosions.

1.INTRODUCTION

In this paper we will discuss the relation between the different types of massive stars and phenomena related to massive stars (the LBV and SN phenomenon) in the Galaxy. For the massive A-M supergiants (further abbreviated as A-M SG), the massive OB type stars, the WR stars we will restrict ourselves to observations of stellar aggregates within 2.5 kpc from the sun (Humphreys and McElroy, 1984; van der Hucht et al., 1988). Evolutionary computations of Maeder and Meynet (1987, 1989) and Maeder (1991) will be used as far as single stars are concerned and the computations performed in Brussels (e.g. reviews of de Loore, 1980 and Vanbeveren, 1991) when close binaries are considered. Section 2 deals with the OB type progenitors of the A-M SG. In section 3 the evolution of these progenitors through the yellow and red supergiants is outlined. The descendants of A-M SG are considered in section 4.

2.THE PROGENITORS OF A-M SG

2.1. The aggregate OB type star sample within 2.5 kpc from the sun.

Figure 1 shows the observed HR diagram of the massive OB type aggregate members within 2.5 kpc from the sun. These observations are compared to evolutionary computations of core hydrogen burning stars of Maeder (1991) with Z=0.04. The time-isochrone of 2.10^6 yrs is indicated as well. The comparison reveals two discrepancies, i.e. neighther the ZAMS nor the width of the core hydrogen burning band (i.e. the location of the TAMS) correspond. The same discrepancies are encountered when evolutionary tracks are used with Z=0.02. We therefore conclude that the discrepancy can not be due to the heterogeneity (of the metallicity) of the observed sample, i.e. the discrepancies are real. There are two possibilities to explain the discrepancies. One can argue that during its formation a massive star remains hidden in the cloud quite some time. When this is the solution for the pauciness of stars younger than 2.10^6 yrs, we have to accept that we are missing 60 % (resp. 31 %, 17 %) of the stars around the 60 $M_{\odot}$ track (resp.25 $M_{\odot}$, 15 $M_{\odot}$), i.e. that accounting for the IMF we are missing 20 % - 30 % of all massive OB type stars due to the fact that they are embedded in their apparent cloud. Although this may solve the ZAMS problem, the TAMS problem remains. A second (promissing) explanation is the possible underestimation of the radiative opacities in the CNO ionisation zone. The need for larger opacities in order to account for the observed properties of OB type stars in the HR diagram was realised already by Bertelli et al. (1984). Larger opacities in the outermost layers of a star will only marginally influence the time evolution of the luminosity of a star, its internal chemical composition, the mass during core hydrogen burning but will shift a star in the HR diagram towards lower T_{eff} values. The evolution of a single star through the yellow and red supergiant phase however may be subjected to major changes which can hardly be forseen.
The possibility for larger opacities is still based on speculation but certainly deserves further efforts.

2.2. The OB type progenitors of A-M SG.

Figure 2 shows the observed HR diagram of all massive aggregate members within 2.5 kpc from the sun; the A-M SG are included with special attention for the location of the cool hypergiants. The evolutionary tracks of massive single stars of Maeder (1991) are shown as well. We conclude that the yellow/red SG result from massive stars with initial ZAMS mass between 8 $M_{\odot}$ and 30 $M_{\odot}$. The lower mass limit depends slightly on the adopted physics in the stellar core which influences the conditions for the ignition of CO ... non-degenerately. Remark that if evolutionary computations without convective core overshooting would be used, the upper mass limit would be shifted to 40$M_{\odot}$. The location of the cool hypergiants indicates that they are descendants of stars in the mass range 20 $M_{\odot}$ - 30 $M_{\odot}$ (40 $M_{\odot}$ with non-overshooting tracks). In the following we will separate the massive OB type stars with initial mass lower than 30 $M_{\odot}$ from the ones with larger initial mass.

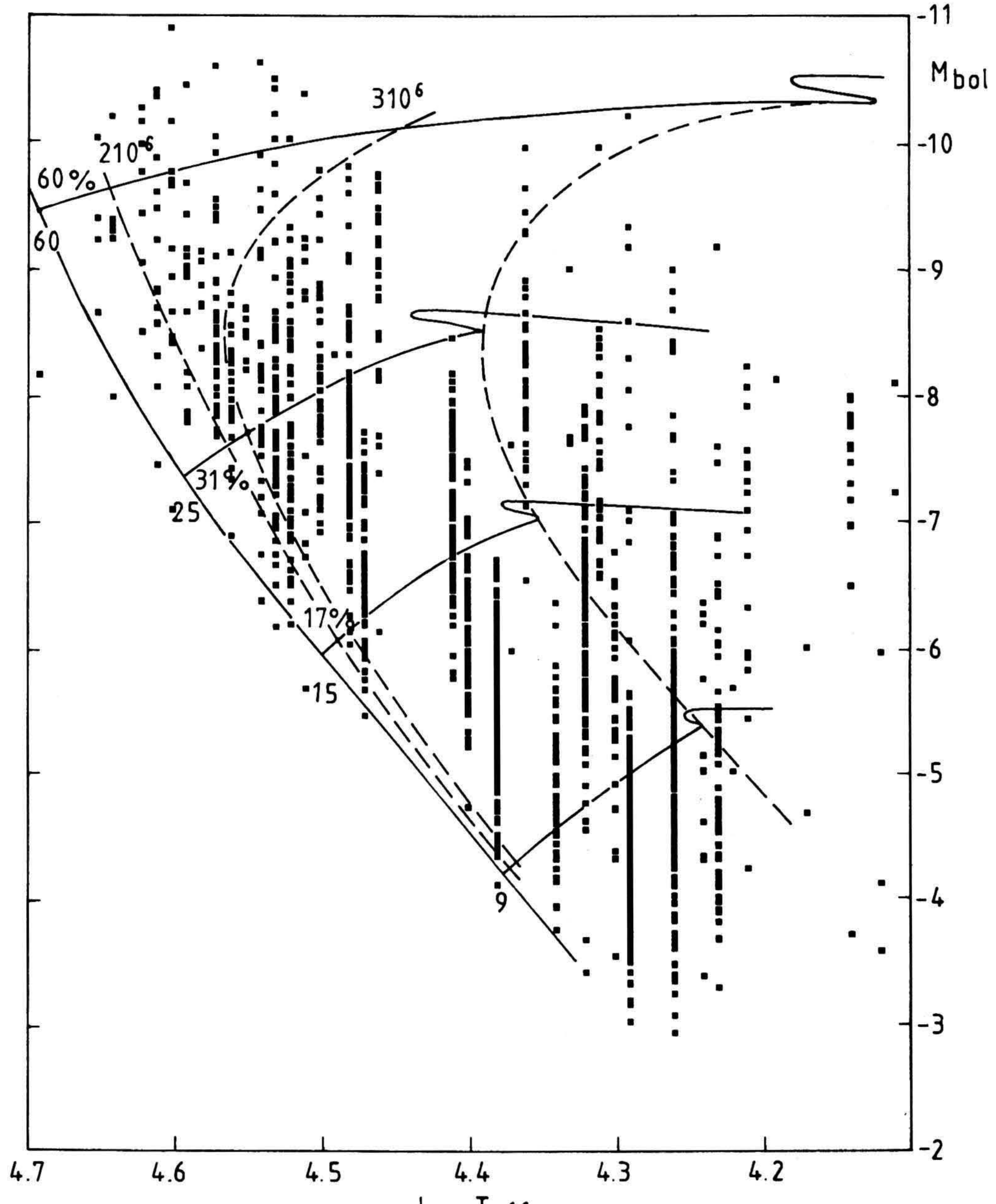

Figure 1. The observed OB type aggregate members within 2.5 kpc from the sun, compared to evolutionary tracks of massive single stars.

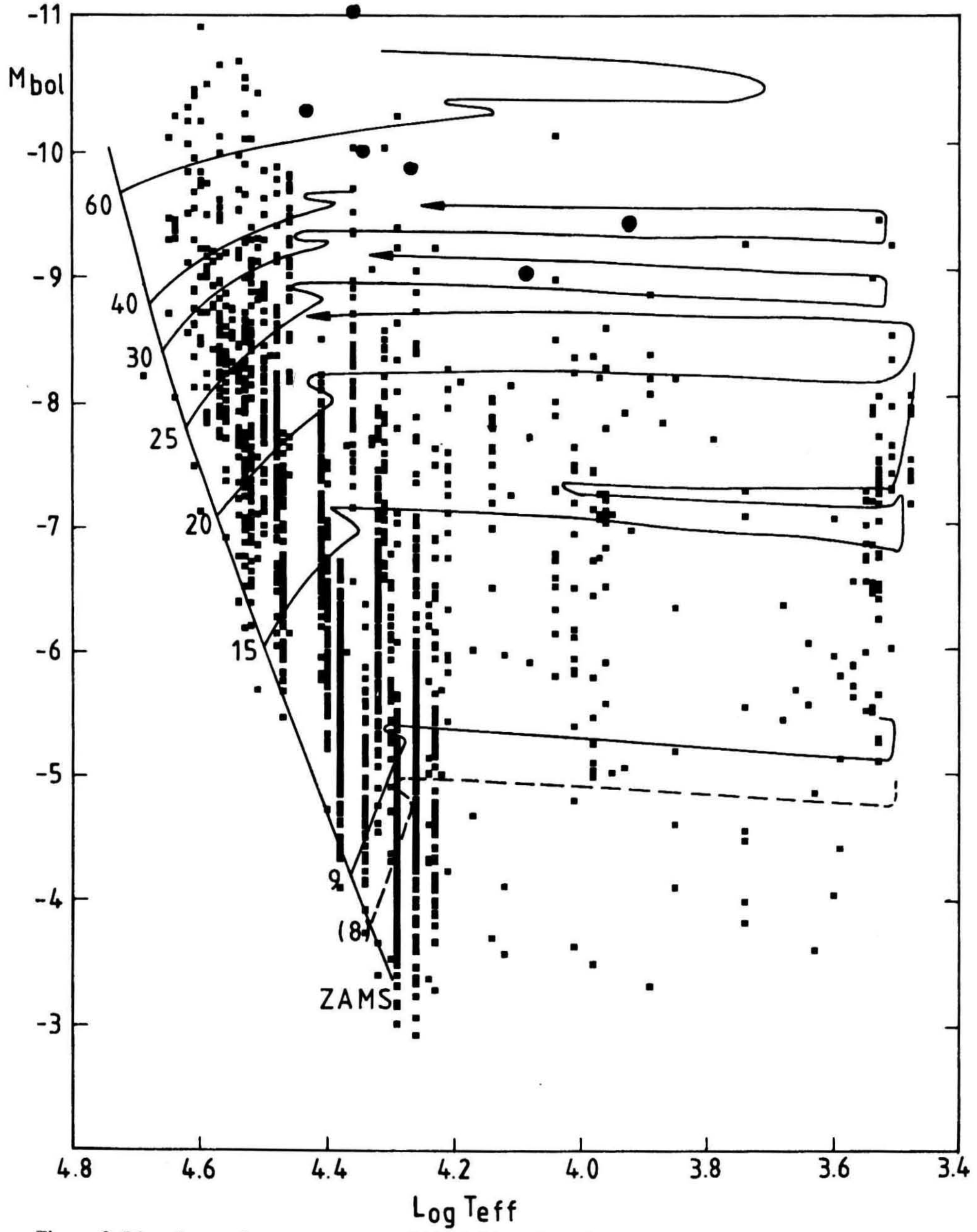

Figure 2. The observed aggregate stars within 2.5 kpc from the sun, compared to evolutionary tracks of massive single stars. The dots indicate the position of the five known LBV's.

3. THE EVOLUTION OF OB TYPE STARS

3.1. The OB type stars with initial mass between 8 $M_\odot$ and 30 $M_\odot$.

Among the OB type stars with initial mass between 8$M_\odot$ and 30 $M_\odot$, three types can be distinguished with a different relation to A-M SG, i.e. the OB type single stars (components of wide binaries are counted as single stars), the OB+OB type close binaries (close means that the evolution of the components will be affected by Roche lobe overflow = RLOF), the OB type accretion stars.

3.1.1. The OB type single stars.

The evolution through the A-M SG phase of OB type single stars with initial mass between 8 $M_\odot$ and 30 $M_\odot$ is critically determined by two processes, the stellar wind mass loss when a star is a red SG and the semi-convection during hydrogen shell/core helium burning. Semi-convection is an instability which occurs in the layers where $\nabla_{ad}<\nabla<\nabla_{Ledoux}$ with ∇ the actual temperature gradient, ∇_{ad} the adiabatic temperature gradient and ∇_{Ledoux} the temperature-molecular weight gradient as described by Ledoux (1947). Three different descriptions exist in order to treat semi-convection, i.e.

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- the chemical profile will reajust according to the time-dependent diffusion approximation described by Langer et al. (1983).

The first two methods are time-independent methods and assume that the timescale for the hydrogen profile reajustment is short compared to the nuclear timescale of the star. For the core hydrogen burning phase this assumption is correct however for the following shorter phases (hydrogen shell burning, core helium burning, helium shell burning, etc.), the assumption is ad hoc and very uncertain. At first sight one may be inclined to prefer the evolutionary results where semi-convection is treated with a time-dependent method. However the diffusion coefficient used in this theory contains an unknown efficiency parameter which again makes the evolution of single stars through the red supergiant phase quite uncertain.
The single star evolutionary computations of the Geneva group are computed using the $\nabla=\nabla_{ad}$ description. The models with initial mass between 8 $M_\odot$ and 20-25 $M_\odot$ develope deep envelope convection during the RSG causing dredge-up of nuclearly processed material and predicting the existence of nitrogen enhanced/CO depleted A-M SG. In stars with initial mass larger than 20-25 $M_\odot$ the stellar wind mass loss during the yellow and red supergiant phase is large enough in order to remove most of the hydrogen rich layers in this way largely reducing the influence of semi-convection (thus also of the way semi-convection is treated). When the atmospherical hydrogen abundance has decreased below a critical value ($X_{atm} < 0.3$ by weight) the star returns to the hot region of the HR diagram eventually forming a WR star (see also section 4).

3.1.2. The primaries of OB+OB type close binaries.

A massive primary of a case A close binary loses most of its hydrogen rich atmosphere as a consequence of RLOF already during core hydrogen burning. After its core hydrogen burning phase this primary evolves directly to the hot part of the HR diagram without encountering an A-M SG phase. Figure 3 shows typical evolutionary tracks of primaries of case B close binaries. The RLOF phase in a massive case B binary lasts for some 10000 yrs; the later the RLOF phase occurs, the more violent is the mass loss process (leading eventually to a common envelope phase), the shorter is the RLOF phase itself. This means that depending on the period of the case B binary a massive primary component may reach the yellow or red supergiant phase but it will stay there for a timescale of the order or smaller than 10000 yrs. As a consequence massive components of case B binaries may encounter an A-M SG phase but it will be a very short lived phase. We then expect very few A-M SG which are descendants of a case B close binary. The evolution of case C systems is still poorly known. Very few computations exist (e.g. Podsiadlowski et al., 1991) and their relation to A-M SG is therefore unclear yet. However among the observed sample of massive binaries, case C accounts for only a minority of the total frequency.
All in all we conclude that massive primaries of close binaries will only marginally contribute to the A-M SG population.

3.1.3. The OB type accretion stars.

The evolution of massive interacting binaries can be summarised as follows:

OB+OB $[M_1+M_2]$ -----> RLOF -----> CHeB+OB
$[M'_1+M'_2=M_2+\beta(M_1-M'_1)]$ --->SN --->CC+OB or OBsingle

β=fraction of matter lost by a mass loser which is accreted by the mass gainer; CHeB=the core helium burning remnant after RLOF. The OB type accretion stars are the M'_2 stars with or without a compact companion (CC) which in the absence of hard X-rays will be hard to detect, i.e. most of these OB type accretion stars will be observed as single stars. Figure 4 shows the evolutionary behaviour of massive stars

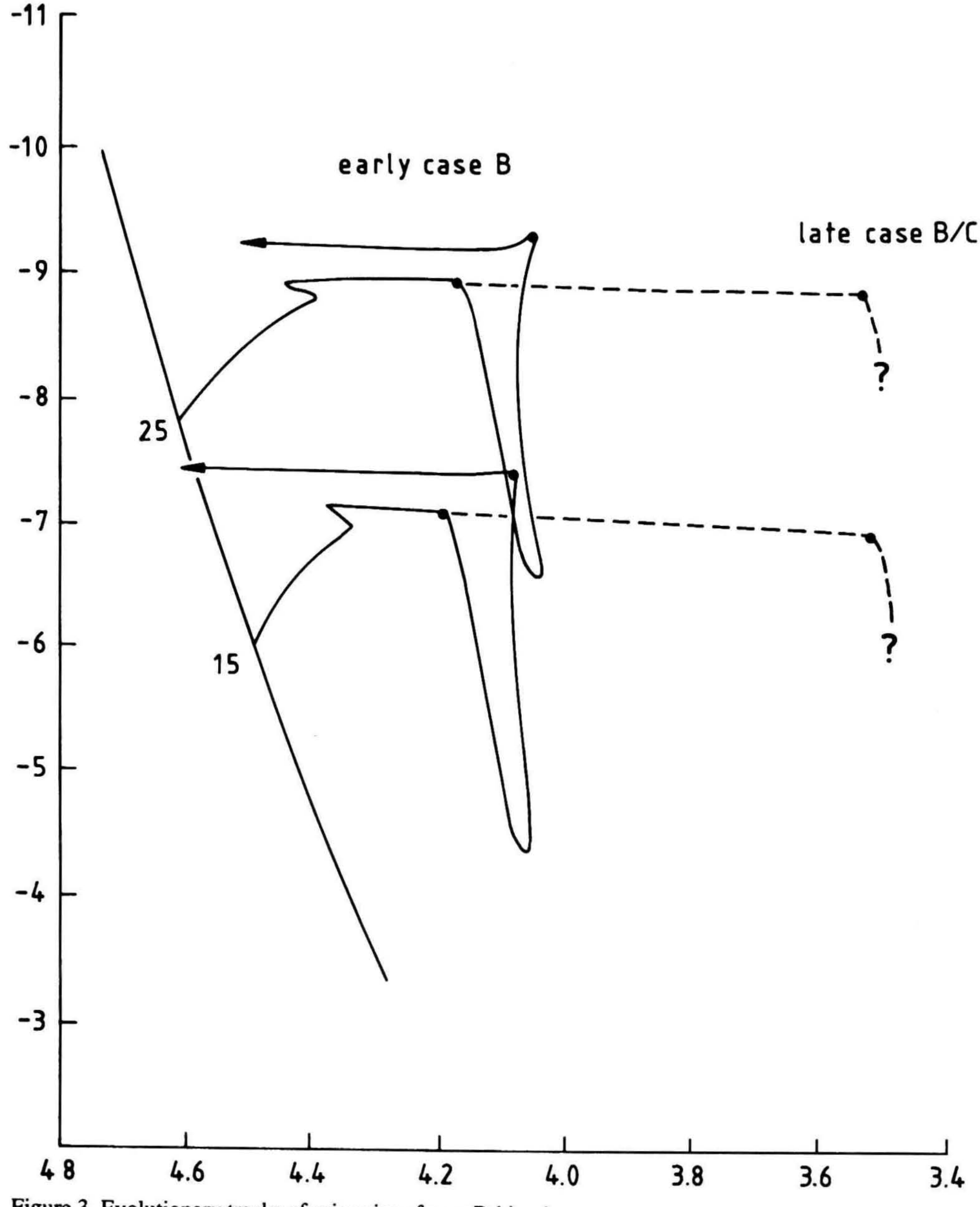

Figure 3. Evolutionary tracks of primaries of case B-binaries.

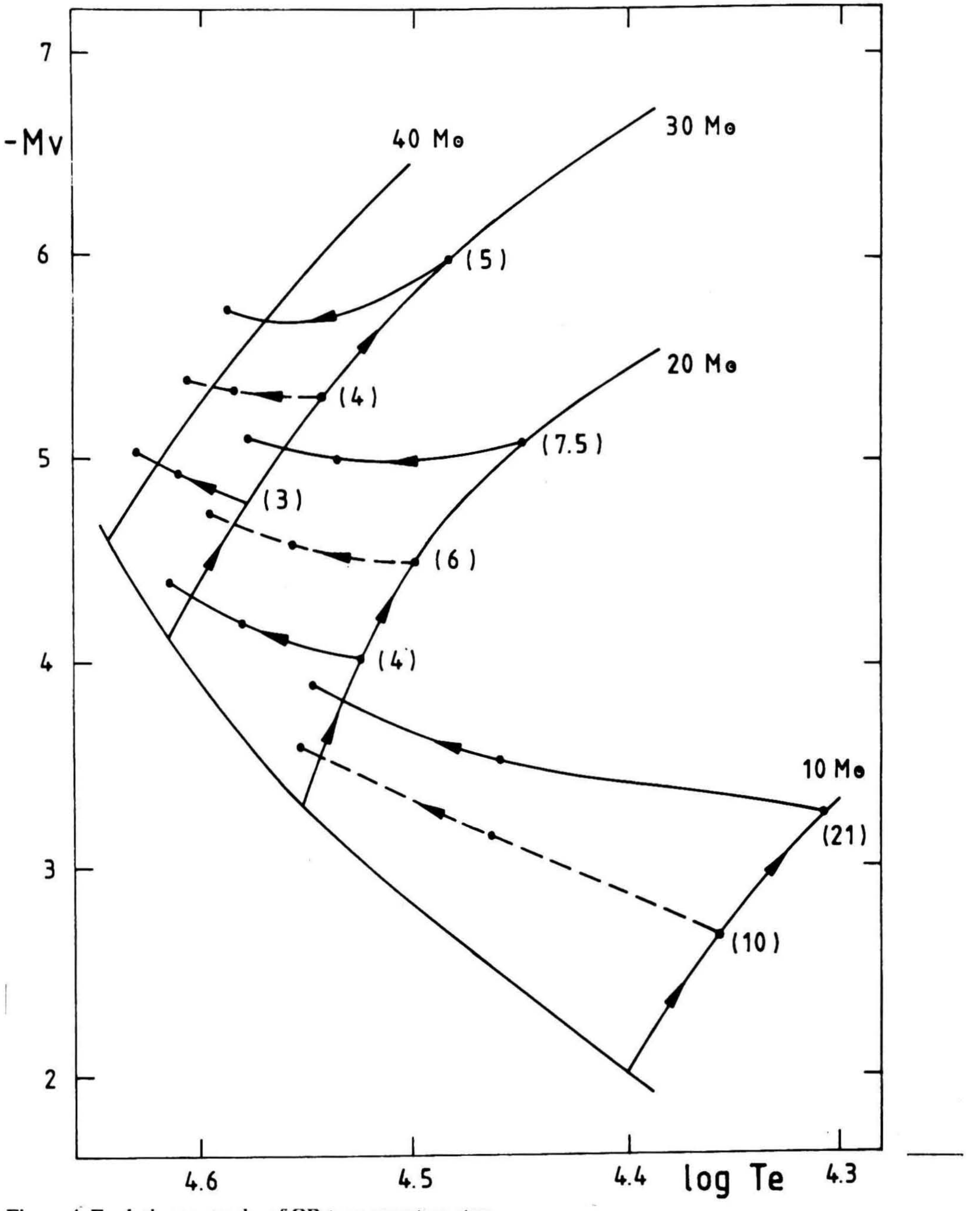

Figure 4. Evolutionary tracks of OB-type accretion stars.

when at a certain moment during their core hydrogen burning phase they are subjected to a mass gain process with mass gain rates of the order of 10^{-4} $M_\odot$ yr^{-1}. As a consequence of accretion the star obviously becomes more massive, the star rejuvenates i.e. the star evolves towards higher T_{eff}, after accretion and relaxation the accretion stars can not be distinguished from normal stars except when they show a runaway character, when they show pronounced CNO anomalies or when they show extreme rotation features (OBe character). Since an accretion star has aquired its present mass not only as a consequence of sta formation but also as a consequence of accretion during a previous RLOF phase, if the number frequency of accretion stars is significant they may pose problems for the determination of the IMF. The number frequency depends on the real IMF, on the unevolved close binary frequency, on the mass ratio distribution of close binaries and on the way the RLOF is treated, i.e. conservative or not. Attempt in order to determine this number frequency have been made by Vanbeveren (1988), Meurs and van den Heuvel (1989). In the worst case but still within observational uncertainty, this number frequency may be as high as 35 % of the total star sample within the 10 - 20 $M_\odot$ range. Accounting for the fact that 33 % of all OB type stars are non-evolved OB+OB type close binaries, we are left with 32 % real single stars only within that mass range. The further evolution of these accretion stars towards the red is still uncertain (Taam et al. 1978; Bodenheimer and Taam, 1984). When the OB type accretion star has a CC and when the orbital energy of the CC star is larger than the binding energy of the atmosphere of the OB type star a spiral-in phase of the CC will occur leading to the removal of the hydrogen rich layers of the OB type star, i.e. a red supergiant phase will not occur. When however the binding energy is larger than the orbital energy the system will enter a common envelope phase, the OB star atmosphere is not ejected and the CC star is simply swollowed by the OB type star. How this will affect the further OB type star evolution towards and through the RSG phase is not known yet.

3.2. OB type stars with initial mass larger than 30 $M_\odot$.

Stars with initial mass larger than 30-40 $M_\odot$ may during their transition from blue to red (during hydrogen shell burning) encounter a phase where they are dynamically unstable causing the LBV phenomenon (see Workshop on 'Luminous Blue Variables', eds. K. Davidson, A. Moffat and H. Lamers, Kluwer Academic Publishers, 1989). The mass loss rates observed in LBVs are so large that when they are applied in an evolutionary code further redwards evolution is stopped and the star never reaches the A-M SG phase (or remains there only for a very short time <= 10000 yrs) and evolves directly into a WR star (see the 60 $M_\odot$ track in figure 1).

4. THE DESCENDANTS OF MASSIVE A-M SG.

4.1. The relation of massive A-M SG and WR stars.

The minimum progenitor mass of WR stars ≈ 20 $M_\odot$ although the bulk originates from stars with initial mass larger than 30$M_\odot$ (Schild and Maeder, 1984; Vanbeveren, 1990, 1991). This means that within the mass range 20-30 $M_\odot$, a star may experience an A-M SG phase and a WR phase. Using the evolutionary computations of Maeder (1991) about 10-15 % of the observed A-M SG within 2.5 kpc from the sun fall within this mass range i.e.

> 10-15 % of the A-M SG within 2.5 kpc from the sun may be WR progenitors. This obviously includes the 'hypergiants'.

Reversing the question we can ask how many of the observed WR stars have had a A-M SG past. About 35 % of all WR stars are components of short period binaries. Accounting for the discussion in section 3.a.2. it is highly unprobable that they have ever been an A-M SG. For the remaining 65 %, using the evolutionary computations of single stars of Maeder (1991) and adopting an IMF ∝ $M^{-2.5}$, it follows that less than 15 % of the WR single stars has ever been a yellow and/or red supergiant. It can thus be concluded that less than 10 % of the total WR sample is descending from an A-M SG phase.

4.2. The relation between massive A-M SG and SN explosions.

All massive stars who still have their hydrogen rich mantle around the core at the end of their life will produce a supernova explosion of type II. This should be the case for all massive single stars with initial mass between 8(9) $M_\odot$ and 20 $M_\odot$, i.e. the majority of the massive A-M SG will explode as type II supernova. Massive single stars with initial mass between 20 $M_\odot$ and 30 $M_\odot$ may lose most of their hydrogen rich atmosphere while being an A-M SG forming in this way a WR stars (section 4.a.). Although these stars may still have a small amount of hydrogen at the end of their life, their SN lightcurve should definitely be different from a classical type II. We propose that the A-M SG with initial mass between 20 $M_\odot$ and 30 $M_\odot$ may be progenitors of type Ib or Ic. We recall that all stars with initial mass larger than 30 $M_\odot$ will produce type I (no hydrogen present) SN explosions. Since all massive components of close binaries (i.e. with initial mass larger than 10 $M_\odot$) will end their life as stripped helium cores due to the RLOF process, also their SN lightcurve should differ from the classical type II, i.e. hydrogen should also here be largely deficient. It is obvious then to realise that among the total sample of SN explosions of type Ib or Ic only a small fraction may have had a massive A-M SG past.

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