THEORETICAL RELATIONS BETWEEN LBVs AND OTHER STARS

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1. Introduction

The so called Luminous Blue Variables (LBVs) form a rather heterogeneous class of very active, luminous (and therefore massive) stars (c.f. R.M. Humphreys, this volume). The following two points are the aim of theoretical work concerning these objects: 1. to know their internal structure from the center up to the atmosphere, i.e. to find out the place of these objects in the course of thermonuclear evolution, or to identify the physical processes which are responsible for the different types of mass loss phenomena, and 2. to conclude which were their preceding evolutionary phases, and to predict their future evolution, i.e. to identify LBV progenitors and descendants, derive their ages, and so on. The basic tool of the theorists is a stellar evolution computer code, which allows to perform evolutionary computations (including different assumptions, which are necessary since several physical ingredients cannot yet be treated from first principles), leading stellar tracks through the part of the HR diagram where LBVs are found. But in this context we meet already a basic problem: in a certain small area of the HR diagram (which may correspond e.g. to some kind of error box) stars of several different types may be identified by the observers, each type may be even devided into several subtypes. Therefore, the correlation of computer models and observed stars is often very difficult or impossible. The various types of stars are mainly classified by spectroscopic criteria, while important "theoretical quantities" as stellar masses or the chemical composition are hard to derive from observations.

A correlation of stellar models with observed stars is also difficult, since there are only few phases of internal evolution in contrast to many different types of stars. For the LBVs, specifically, we will argue in the next Section that their internal evolutionary stage is that of shell hydrogen burning, i.e. the contraction phase between central H- and He-burning, but the variety of LBV subtypes is quite large (see again: R.M. Humphreys, this volume). Consequently, in the case of the LBVs we have to conclude that besides the interior evolutionary state one further parameter must be responsible for the diversity of the LBV phenomena. One may of course think about binarity, rotation, magnetic fields, etc., things which may certianly be important in specific cases. In the present paper we will, however, investigate the most simple possibility, which is that the (actual or initial) stellar mass has some effect on the display of a massive star in the LBV phase. In Section 3

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we will therefore look for structural differences in stellar models of different masses in the H-shell burning phase. The question, whether some LBVs may be post-Red Supergiants (RSGs), which would correspond to the central helium burning evolutionary phase, is explicitly discussed in Sect. 4.

Concerning the comparison of theoretical stellar sequences with LBV observations, a further important point is the following: it exists (to our knowledge) no stellar evolution calculation leading through the LBV regime of the HR diagram which produces dynamically unstable stellar models. This means that the physics which is responsible for the violent outburst phenomena observed in several LBVs (cf. K. Davidson, this volume) is not included in any stellar evolution calculation. There are two possibilities about the origin of these outbursts: either they are "surface phenomena", i.e. the responsible process acts in the stellar atmosphere, or the outbursts are initiated in the deep interior of the star. In the first case the problem should be solved by stellar atmosphere physicists, and the solution will be implemented as a boundary condition in the stellar structure code. The second case means, however, that the stellar models include unjustified simplifications. Since it seems more likely that the ejection of $\sim 0.1 M_\odot$ (as in the case of η Car) is triggered at the bottom of the shell rather than at its outer surface, it is necessary to look for processes in the deep stellar interior, which may be responsible for such events. A possible candidate is presented in Section 5.

Finally, in Section 6 we summarize our results and present a coherent picture for the evolution of massive stars including the LBV stage as a key phase.

2. The evolutionary phase of LBVs: H-shell burning

In principle it is possible that massive stars evolve to the blue side of the zero age main sequence (ZAMS) already during core hydrogen burning, e.g. in the case of huge convective core overshooting (Langer & El Eid, 1986; Prantzos et al., 1986) or rotational induced mixing (Maeder, 1987). However, in this case the stars never return to the red side of the ZAMS and can thereby obviously never reach the LBV stage. For this reason we concentrate on the other alternative, i.e. the case where no bluewards evolution occurs during core hydrogen burning, which is obviously realized in nature since LBVs exist, and which is the result of stellar evolution calculations with "standard assumptions" (cf. e.g. Maeder & Meynet, 1987).

In this case, all massive stars (when computed with mass loss during core H-burning) show a strong tendency to move towards the Hayashi line in the HR diagram after central hydrogen exhaustion (cf. Langer & El Eid, 1986, Maeder & Meynet, 1987), i.e. they would become RSGs if not something (preferentially mass loss at huge rates) would prevent them, and ignite He-burning at the RSG branch. Now, the RSG configuration is forbidden for stars more luminous than $\sim 10^{5.8} L_\odot$ for observational reasons (cf. R.M. Humphreys, this volume). Therefore, something must make the stars stop at the Humphreys-Davidson (HD) limit in the HR diagram, causing thereby the LBV phenomenon. This means that helium burning did not yet ignite in this situation. In other words, LBVs (at least those with $\log L/L_\odot \gtrsim 5.8$) are in the shell hydrogen burning phase of evolution. This means specifically, that the whole star (and not only the stellar envelope) is completely out of thermal equilibrium. Consequently, the whole internal structure changes very rapidly, on a thermal timescale, i.e. $\sim 10^4\,yr$. Note that this is the same order of magnitude as the LBV lifetime estimated from observations (cf. Lamers, this volume), which may be an indication for the core contraction being the virtual origin of the LBV phenomenon (cf. next Section).

3. How the H-shell burning phase affects the further evolution

After central hydrogen depletion a star performs a short phase of overall contraction, which soon leads to the ignition of a hydrogen burning shell around the hydrogen exhausted core. Up to central helium ignition, this shell is the only nuclear energy source of the star. While the contracting hydrogen exhausted core does not react upon the ignition of the H-shell, this has two effects on the outer layers:

1) The whole envelope, i.e. the layers above the shell, start to expand, which makes the star becoming a supergiant, and which is accompagnied by the formation of a more or less extended convection zone close to the surface. (This convection zone may well be relevant to the LBV phenomenon; see Section 5).

2) Just above the H-burning shell an intermediate convection zone (ICZ) forms in layers, which contain gradients of the chemical composition, left behind by the shrinking convective core during central hydrogen burning.

While effect 1) will be discussed in Section 5, we will focus here on the second effect: The formation of the ICZ leads to changes of the chemical profiles. Though part of this zone, especially in stars with $M_{ZAMS} \lesssim 40\,M_\odot$, may be semiconvective rather than convective (cf. Langer, 1985, for a discussion), we will assume here for simplicity, that the whole superadiabatic region becomes rapidly chemically homogeneous. When we designate the mass of the ICZ as ΔM_{ICZ}, and the hydrogen mass fraction which is established by the mixing processes in that zone as X_{ICZ}, we notice in stellar evolution computations, that both quantities are monotonous functions of the stellar mass (or ZAMS mass): ΔM_{ICZ} is increasing and X_{ICZ} is decreasing with increasing stellar mass. We found e.g. for $M_{ZAMS} = 100\,M_\odot$: $\Delta M_{ICZ} = 20\,M_\odot$, $X_{ICZ} = 0.23$, and for $M_{ZAMS} = 30\,M_\odot$: $\Delta M_{ICZ} = 7\,M_\odot$, $X_{ICZ} = 0.50$.

Now it is important to recall, that the redwards evolution is halted at the HD-limit in the LBV stage due to enormous mass loss. Evolutionary calculations show, that the redwards trend itself is stopped, when sufficient mass has been removed in order to drop the surface hydrogen mass fraction below some critical value X_{crit}. In this situation we get a bifurcation of the evolution (cf. Langer, 1987):

In the case $X_{ICZ} > X_{crit}$, the LBV mass loss has to last until all the envelope material up to the bottom of the former ICZ is lost, which means that the He-core itself almost appears at the stellar surface at the end of the LBV phase. This scenario, which is a possibility for stars with $M_{ZAMS} < M_{crit}$ (M_{crit} being defined by the condition $X_{ICZ}(M_{crit}) = X_{crit}$), leads directly to low mass WNE stars as LBV descendants.

In the second case, i.e. $X_{ICZ} < X_{crit}$, the redwards trend is stopped and the LBV phase finished when the top of the H-plateau established by the former of the ICZ reaches the stellar surface. This scenario, which may apply for $M_{ZAMS} > M_{crit}$, results in massive WNL stars as LBV descendants.

Both cases lead to quite different average LBV masses. The first case ($X_{ICZ} > X_{crit}$) applies to the less massive stars considered here, but implies a larger total amount of mass lost in the LBV stage, since the whole former ICZ has to be ejected, while the second case applies to the most massive stars and does not require too much mass to be ejected in the LBV stage, since the former ICZ is kept, forming the envelope of the WNL star lateron.

In summary, we have two evolutionary possibilities for massive stars which enter the LBV phase:

$M_{ZAMS} < M_{crit}$: O-star → low mass LBV → WNE
$M_{ZAMS} > M_{crit}$: O-star → massive LBV → WNL

The exact numbers for M_{crit} and X_{crit} depend greatly on the input physics used in stellar evolution calculations. For the two examples mentioned above we find: $M_{ZAMS} = 30\,M_\odot$, $X_{ICZ} = 0.50 > X_{crit} \Rightarrow M_{LBV,min} = 12\,M_\odot$, and $M_{ZAMS} = 100\,M_\odot$, $X_{ICZ} = 0.23 < X_{crit} \Rightarrow M_{LBV,min} = 60\,M_\odot$, indicating that $30\,M_\odot < M_{crit} < 100\,M_\odot$, and $0.23 < X_{crit} < 0.50$ for standard assumptions.

4. Do post-RSG LBVs exist?

According to R.M. Humphreys (this volume) and others, some LBVs exist with luminosities below the upper luminosity limit for RSGs. For these objects, both evolutionary connections, LBV → RSG and RSG → LBV, are therefore not prohibited by observations.

As for the second possibility, since the star enters in this case the LBV region of the HR diagram the second time, one might wonder why the LBV phenomenon did not occur already on the way towards the RSG branch. However, we note that several physical quantities of a star returning from the RSG branch may be different compared to its state on the way becoming a RSG, though the HR diagram location may be almost identical. First of all it is important, that all stars, when they reach the Hayashi-line, increase their luminosity considerably. This means that a star is more luminous on its way back to the blue side of the HR diagram than it was on its way towards the red side. The relative luminosity increase is larger for less massive stars and may be of the order of 30% for stars with luminosities close to the observed upper luminosity limit for RSGs (cf. Maeder & Meynet, 1987), the numbers depending, however, greatly on the considered internal mixing processes (Langer et al., 1985). It may therefore be possible that a star in its pre-RSG state is not sufficiently luminous in order to encounter the LBV instability, but as a post-RSG its luminosity is high enough.

Further changes that occur at the RSG branch are a modification of the envelope chemical composition due to convective dredge-up, and a considerable decrease of the envelope mass due to the large mass loss of RSGs.

In summary, for a narrow mass range the evolutionary path O-star→RSG→LBV seems possible, and also the alternative O-star→LBV→RSG cannot be excluded for those stars. One may speculate whether the relatively low luminous cool LBVs mentioned by C. de Jager (this volume) are connected with such scenario.

As mentioned above, stellar evolution calculations do not result in dynamically unstable stellar models in neither of the two possibilities (see, however, A. Maeder, this volume). In one sequence we found, however, a thermally unstable situation for post-RSG models at about the LBV position in the HR diagram (cf. Langer & El Eid, 1986), which was related to an adjustment of the H-burning shell, and a similar small loop at $\log T_{eff} \simeq 4.3$ is visible in the $60\,M_\odot$-track of Maeder (1981).

Whether this is a hint towards the existence of post-RSG LBVs or not cannot yet be answered.

Finally, we want to specify a few points, by which post-RSG LBVs may be distinguished observationally from "usual" LBVs. First of all, the slow and dense RSG wind might be swept up by the faster LBV wind, giving rise to the formation of some kind of ring nebula (reminding us to AG Car). And secondly, post-RSG LBVs should be relatively old as compared to normal ones (cf. Lortet and Testor, 1988, for discussion), since they originate from lower ZAMS masses and are additionally more evolved: they are within the central helium burning phase, while "normal" LBVs are in the H-shell burning phase (cf. Section 2).

5. A possible mechanism for violent shell ejections

In Section 3 we have already mentioned, that one consequence of H-shell burning is the expansion of the stellar envelope. When the surface temperature drops to values of the order of 15 000 K, the opacity in part of the envelope has increased so much, that a convection zone forms, which is located close to the stellar surface. In context with the LBVs it is now interesting, that the convective velocity v_{conv} — i.e. the average velocity of the convective eddies — becomes very large, i.e. very close to the velocity of sound v_{sound}. If the equations of the standard mixing length theory (MLT; cf. e.g. Kippenhahn et al., 1967) are applied, even supersonic convection velocities are the result. Note, however, that the MLT is in principle not applicable to such a situation, since dissipative terms are not included. In a real star, the sound velocity may not be exceeded by convection.

However, it is clear that the ratio $r = v_{conv}/v_{sound}$ becomes close to unity in the considered convection zone. The resulting turbulent pressure P_{turb}, which can be estimated according to $P_{turb}/P = \frac{\pi}{2}\Gamma_1 r^2$, will therefore be of the order of the gas- plus radiation pressure P, since $\Gamma_1 = (\partial \ln P/\partial \ln \rho)_{ad}$ is also of order unity. In a study of a $100\,M_{\odot}$-ZAMS sequence, computed with standard assumptions analogue to that of Langer & El Eid (1986), Kiriakidis (1987) finds the turbulent pressure to have local maxima in the recombination regions of hydrogen and helium. Furthermore, the maximum turbulent pressure as a function of the stellar effective temperature is largets at $T_{eff} \simeq 10\,000\,K$, which coincides well with the location of the LBVs. The acceleration due to turbulent pressure, which is proportional to dP_{turb}/dr, is found to have a large maximum at the hydrogen recombination front, which lies $\sim 0.06\,M_{\odot}$ deep below the surface within the star in the model with $T_{eff} = 10\,000\,K$; an ammount of mass which might correspond to the shells ejected by several LBVs. Note, however, that the computations mentioned above are not selfconsistent in the sense that the turbulent pressure has not been taken into account in the models. Selfconsistent computations would be highly interesting and are under investigation in Göttingen.

6. Summary: LBVs as a stage of massive stars evolution

According to the observed luminosities of LBVs it is clear, that a lower ZAMS mass limit for LBV formation exists, which we want to designate as M_{LBV}. The possibility of an upper ZAMS mass limit for LBV formation — let us call it M_{Conti} — cannot be excluded, but since η Car is regarded as an LBV it should be $M_{Conti} > M_{ZAMS}(\eta\,\mathrm{Car})$. If M_{Conti} exists, stars with ZAMS masses above that limit evolve into WNL stars already during central hydrogen burnig (cf. Section 1).

In Section 3 we have shown the possibility of the existence of a critical ZAMS mass M_{crit} such that stars above that limit form massive LBVs which finally turn into WNL stars, while stars below it form low mass LBVs, which evolve directly into WNE stars. From the definitions above and the results of Section 3 we conclude that $M_{LBV} < M_{crit} < M_{Conti}$.

Finally, we explored the possibility of post-RSG LBVs in Section 4, and found that stars with ZAMS masses close to but above M_{LBV} might follow this scenario. (Let us call the upper mass limit for RSG formation M_{RSG}.)

Altogether we see that evolutionary connections in the upper HR diagram may be quite complex, as much more in the case where the different Wolf-Rayet subtypes are considered (cf. the "phase diagram" in Langer, 1987). As function of increasing ZAMS mass they may be listed as follows:

$8\,M_\odot < M_{ZAMS} < M_{LBV}$: O,B-star → supergiant → SN
$M_{LBV} < M_{ZAMS} < M_{RSG}$: O-star → RSG → low mass LBV → WNE (→ WC) → SN
$M_{RSG} < M_{ZAMS} < M_{crit}$: O-star → low mass LBV → WNE (→ WC) → SN
$M_{crit} < M_{ZAMS} < M_{Conti}$: O-star → high mass LBV → WNL (→ WC) → SN
$M_{Conti} < M_{ZAMS}$: O-star → WNL (→ WC) → SN

Note, however, that still much theoretical and observational work is required in order to derive values for the critical masses and to discuss other possible evolutionary scenarios.

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DISCUSSION

Sreenivasan: I am glad to see your tracks for a 100 $M_\odot$ model. It does not seem to have been generally appreciated that small changes in the mass-loss rates (factors of 2 or 3) can change evolutionary tracks significantly. One can turn tracks around near $T_{eff} \sim 10^4$ K only with large core sizes and high mass-loss rates. Also, by increasing mass-loss rates abruptly, one can reverse the direction of a track. Precisely what rates did you use?

Langer: I used the mass-loss formula of Lamers (1981, *Ap.J.* **245**, 593), and further details of this track can be found in *Astron. Astrophys.* **167**, 265. But I would not characterize a change in mass-loss rate by a factor of 2 or 3 as small.

Maeder: You stated that a very massive star experiences nothing remarkable along its redward track. I have just the opposite opinion. During redward evolution, the models show that the luminosity becomes supercritical in the layers where the opacity peak is located; this is the sign that static models are no longer valid. I think that this is a major event, possibly related to the essence of the LBV phenomenon.

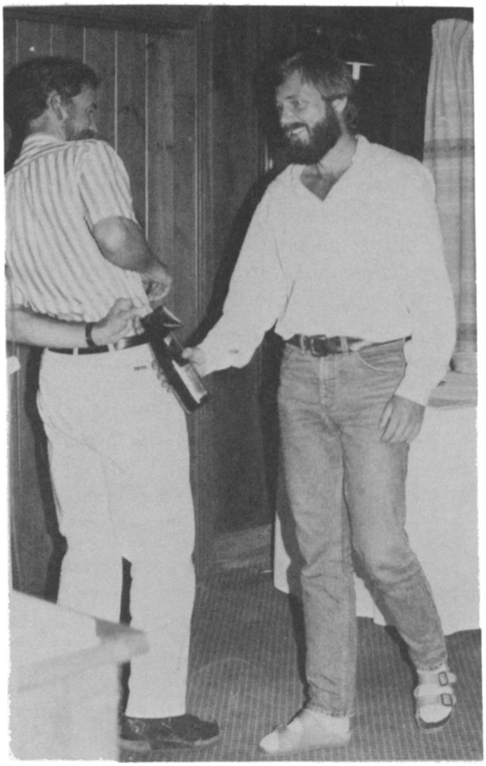
Langer: In the stellar evolution sequences that I have computed, the Eddington luminosity is never actually exceeded within the star while moving toward the Hayashi line. The density inversion in the envelope that you referred to may or may not occur in models, depending on the way convection is treated. In a real star, a density inversion may be prevented by the Rayleigh-Taylor instability. Of course something has to happen when the star crosses the H-D limit redwards, but what I meant to say is that the relevant physics is not yet included in any stellar evolution calculation.

De Groot: I cannot judge whether these oscillations along the blueward track are real or not, but I want to note that P Cygni's basic parameters place it exactly in this part of the H-R diagram for the appropriate mass. I wonder if this is true also for other LBV's; if so then this could be evidence for the reality of these oscillations in the evolutionary track.

Langer: It is of course remarkable that the thermal oscillations occur at the "right place" in the H-R diagram. However, one has to try to understand the physical processes in order to assess evidence that this is related to the LBV phenomen.

Sreenivasan: I agree with Maeder that something remarkable happens to the right of the sloping Humphreys-Davidson line, but I think that we are remarkably ignorant of precisely what that is. We just do not know the physics of what happens there. The effect of opacities on the Eddington luminosity seems clear, but how that relates to the stellar wind of supergiants in that temperature range is not clear. One cannot simply scale upwards the solar wind type of mass loss.

Langer: I agree completely; but, as you say, a proper theoretical treatment has not yet been applied in any calculation.



Moffat and Langer,
demonstrating the contrast
between observational
and theoretical approaches