Pre-Planetary Nebulae and R Corona Borealis Stars

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1. INTRODUCTION

With the advent of the IRAS satellite a completely new class of stellar objects became evident; viz., objects which are obviously in a rapid transition from the very tip of the asymptotic giant branch (AGB) into the planetary-nebulae region. These so-called pre-planetary nebulae (PPN) are characterized by stellar spectra indicative of supergiants mainly of F and G spectral types in conjunction with a large infrared excess due to a cool circumstellar dust shell. At the same time theoretical calculations through the AGB, with the inclusion of mass loss, and also through the following evolutionary stages down to the white-dwarf sequence, became available (Schönberner 1979, 1983; Wood and Faulkner 1986). These calculations predict evolutionary lifetimes of several 1000 years in the transition region between the tip of the AGB and the planetary-nebulae region. Thus a direct comparison between theory and observation now appears possible in the very early phase of this post-AGB evolution.

Another group of stars which occupy about the same region of the H-R diagram as PPNs, the R CrB stars (RCB), are well known to all astronomers, and their peculiarity has been known for more than 50 years. They are, however, one of the least studied groups of stars, and their evolution is not yet at all clear. As will be shown later in this review, they will most likely also evolve towards the final white-dwarf stage.

This review is organized as follows. After a short summary of post-AGB evolution, the theoretical predictions are compared with very recent observations of PPNs. Then follows a short account of our present knowledge about RCBs and a detailed comparison between the properties of both types of stars. Finally, a few statements about the evolution of RCBs are made.

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2. TERMINATION OF THE AGB EVOLUTION

It is well established from evolutionary calculations that the luminosity of a giant at the Hayashi limit depends practically only on the mass, M(H), of the hydrogen-exhausted core (e.g. Paczynski 1970; Kippenhahn 1981). This statement holds also for stars on the AGB since it is mainly hydrogen burning that determines the overall course of evolution; i.e., L = L(H) for more than 80% of the evolutionary time. This luminosity, L(H), in turn determines the growth rate, $\dot{M}(H)$, of the core according to

$$\dot{M}(H) = L(H)/(X\ E(H)) \ ,$$

where E(H) (= 6.3×10^{18} erg/g) is the energy released per gram of hydrogen, and X is the hydrogen mass fraction of the stellar envelope. For a typical core mass M(H) = 0.6 M☉, $\dot{M}(H) = 10^{-7}$ M☉/yr. This stellar core is already a very hot (pre) white dwarf, whose further evolution proceeds independently of the envelope as long as the latter contains sufficient mass ($M(e) \approx 10^{-4}$ M☉) to maintain the burning temperature in the hydrogen shell. The evolutionary tracks of AGB stars are determined by envelope expansion as the core M(H) grows by mass addition, and finally by contraction as the envelope M(e) drops below ≈ 0.05 M☉.

While the nuclear evolution of an AGB star is controlled by the core mass M(H), the total lifetime on the AGB is determined by mass loss from the surface of the star. This is a consequence of the observed stellar winds with mass-loss rates up $\dot{M}(w) \approx 10^{-4}$ M☉/yr for very luminous AGB stars (e.g. Knapp 1985; Kleinmann, this conference). Even if most stars do not reach such large rates, it is clear that always $\dot{M}(w) \gg \dot{M}(H)$ on the upper AGB (at the AGB limit, $\dot{M}(H) = 6 \times 10^{-7}$ M☉/yr). Thus, the lifetime at the tip of the AGB is very short (planetary-nebula formation!), and the subsequent post-AGB evolution is completely determined by the stellar structure at the AGB tip, which in turn is a function of the thermal-pulse cycle phase (cf. Iben 1984; Schonberner 1979, 1983).

Two evolutionary modes of an AGB star have to be considered -- the hydrogen-burning and helium-burning mode. Hydrogen burning makes up about 80% of the evolutionary time on the AGB and is characteristic of the majority of central stars (cf. Schonberner 1981). The star is in thermal equilibrium, and since there exists a one-to-one anticorrelation between residual envelope mass M(e) and effective temperature T(eff), the contraction time scale for the transit from the AGB tip to higher effective temperature is

$$t = -M(e)/\dot{M}(e) = M(e)/(\dot{M}(H) + \dot{M}(w)) \ .$$

For T(eff) < 10,000 K, M(e) < 0.001 M☉, and with $\dot{M}(H)$ = const, the transition time scale is mainly determined by the wind term $\dot{M}(w)$,

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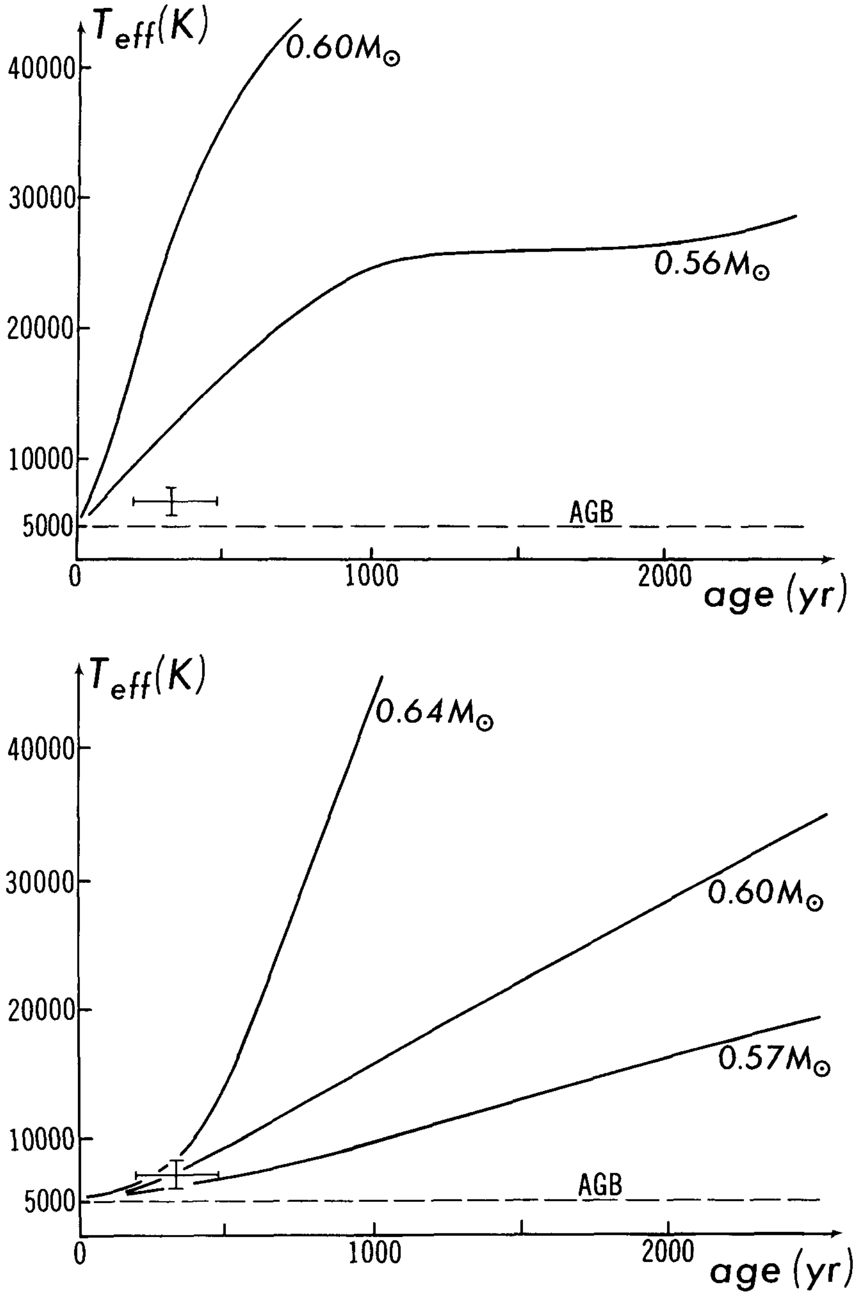

Figure 1. Post-AGB evolutionary tracks of different models displayed in a T(eff)-age diagram. Age zero corresponds to 5000 K. The upper part contains helium-burning models, taken from Wood and Faulkner (1986, 0.6 M⊙) and Schönberner (unpublished, 0.56 M⊙). The lower part shows the hydrogen-burning models of Schonberner (1979, 1983). In both parts the position of IRAS 18095+2704 is indicated (Hrivak et al. 1988).

especially in the vicinity of the AGB, where still $\dot{M}(w) > \dot{M}(H)$. Thus the evolutionary "speed" $\dot{T}(eff)$ of hydrogen-burning AGB remnants is practically determined by the size of post-AGB mass-loss rates and their variation with increasing effective temperature.

After a flash of the helium-burning shell, however, the star is completely out of thermal equilibrium and, should it be forced by mass loss to leave the AGB (planetary-nebulae formation), contracts according to the thermal time scale of the envelope. In this particular case, however, envelope means all matter above the helium-burning shell. It is difficult to estimate the transition time, but the computations show that it is much shorter than in the hydrogen-burning case (see Fig. 1).

Only two sets of evolutionary calculations with consideration of mass loss are available in the literature: Schonberner (1979, 1983) and Wood and Faulkner (1986). Schonberner (1983) assumed $\dot{M}(w) = 10^{-4}$ M☉/yr for $T(eff) \lesssim 5000$ K and $\dot{M}(w) = \dot{M}(w)$ (Reimers) otherwise, whereas Wood and Faulkner assumed $M(w) = 10^{-5}$ M☉/yr for $T(eff) < 6300$ K and $\dot{M}(w) = 0$ otherwise. In both cases we have $\dot{M}(w) \gg \dot{M}(H)$ in the vicinity of the AGB, and the mass loss affects a fast departure from the tip of the AGB. An illustration of the evolutionary speeds of different post-AGB models is presented in Fig. 1, where the effective temperatures vs. post-AGB ages are plotted. Age zero corresponds to 5000 K where the high AGB-mass-loss rate is assumed to cease. It is evident that a helium-burning model evolves much faster than a hydrogen-burning model of the same mass (cf. discussion above). For a typical remnant of 0.6 M☉, we find $\dot{T}(eff) \approx 40$ K/yr for the helium-burning and $\dot{T}(eff) \approx 10$ K/yr for the hydrogen-burning case. Please note that the curves for the hydrogen-burning models, taken from Schonberner (1979, 1983), contain the wind term $\dot{M}(w)$ according to Reimers (1975). This term is still important as long as $T(eff) < 10{,}000$ K (cf. Schonberner 1983).

3. PRE-PLANETARY NEBULAE

Stars close to the end of their AGB evolution are completely obscured by optically thick, relatively cool dust shells as the consequence of high mass-loss rates. When such a star leaves the AGB, the mass-loss rate will ultimately drop because the stellar surface is shrinking and warming. The dust shell continues to expand, but since there will not be sufficient replenishment of warm dust at the inner boundary of the shell, it becomes cooler and optically thinner until finally the stellar remnant may shine through (Bedijn 1987). By means of the IRAS satellite, several well-known supergiants which seem to fit this scheme have been observed. Mainly of spectral types F and G, these stars exhibit large IR excesses indicative of very cool ($T(d) \approx 100$ K) dust shells (Parthasarathy and Pottasch 1986; Likkel et al. 1987; Pottasch and Parthasarathy 1988). They are obviously low-mass remnants from the AGB instead of being massive young stars as one might judge from a first look at their spectra (cf. Luck and Bond 1984).

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The IRAS data base also revealed the existence of non-variable OH/IR stars with properties just as described above: the peak of the IR emission is shifted further to longer wavelengths, and at $\lambda < 10$ μm the emission from the central remnant dominates the spectrum (Habing et al. 1989). These results suggest that pulsations are responsible for triggering high mass-loss rates. Recent theoretical calculations by Bowen (1988; also this conference) indicate the importance of periodic shocks caused by radial pulsations for increasing the extent of the stellar atmosphere and facilitating the formation of dust. Radiation pressure on dust grains then leads to high mass-loss rates. As a AGB giant becomes hotter by evolving off the AGB, pulsations will become less severe and will ultimately stop, leading to a decrease of the mass-loss rate.

Thus IRAS observations of non-pulsating OH/IR stars provides, for the first time, the opportunity to study the departure of stars from the AGB. By matching a dust-shell model to the observed IR flux one can estimate the inner dust-shell radius. Assuming a typical stellar luminosity of, say 6000 $L_\odot$, and with a typical expansion velocity of, say 15 km/s, one gets the time since the heavy mass loss ceased. The stellar temperature can be estimated by fitting the stellar component by a blackbody. Hrivnak et al. (1988) investigated the OH/IR source IRAS 18095+2704 this way and found a stellar component of T(eff) = 7000 K and an age of inner dust-shell boundary of $\approx$ 300 yr. The position of this object is shown in Fig. 1, and it appears that its position is consistent with hydrogen-burning model tracks of about 0.6 $M_\odot$.

It would be very useful to investigate more objects of this kind in order to improve our knowledge about the details of the transition from the AGB to central stars of planetary nebulae. Furthermore, the existing observations indicate that the space between the stellar surface and the inner dust shell is not empty. A small IR excess for $\lambda < 10$ μm hints at the existence of ongoing dust formation. A knowledge of this post-AGB mass-loss rate is very desirable since, as explained in the previous section, $\dot{M}(w)$ together with the nuclear term, $\dot{M}(H)$, determines the evolutionary speed.

A study of a larger sample of PPNs found by IRAS is presently underway (Van der Veen, private communication). Preliminary results are as follows: The central objects of these PPNs have effective temperatures ranging from 5,000 K to 20,000 K. Obviously the strong AGB mass loss continues until the remnant reaches about 5000 K. The distribution T(eff) vs. age corresponds to a mean evolutionary rate $\dot{T}(eff) \approx 10$ K/yr, in good agreement with the predictions of the hydrogen-burning post-AGB models of $\approx$ 0.6 $M_\odot$ by Schonberner (1979) (cf. Fig. 1). As already mentioned in the previous section, these computations considered a modest mass loss (Reimers 1975) with $\dot{M}(w) \gtrsim \dot{M}(H)$ ($\approx 10^{-7}$ $M_\odot$/yr). The consistency of Van der Veen's results with Schonberner's evolutionary calculations would then give the first hint that post-AGB mass-loss rates are of the order of the burning rates, i.e. $\dot{M}(w) \approx 10^{-7}$ M⊙/yr.

4. THE R CORONA BOREALIS STARS

A comprehensive review on the evolutionary status and origin of RCB stars as a subgroup of extremely hydrogen-deficient stars is given in Schonberner (1986) and shall not be repeated here. Instead, in this review emphasis is put on certain aspects that have some bearing on PPNs. A few basic properties of RCBs, however, have to be mentioned first.

(1) RCBs are single, relatively cool supergiants with $L/M \approx 10^4$ L⊙/M⊙.

(2) They have an inert, electron-degenerate C/O core, growing by helium shell burning at a rate given by

$$\dot{M}(He) = L(He)/(Y\ E(He)) \ ,$$

where $E(He) = 6 \times 10^{17}$ erg/g and $Y = 1-Z$.

(3) Their extended envelope is virtually hydrogen-free, H/He 10^{-4}, and carbon is the most abundant element next to helium, C/He ≈ 0.003 ... 0.03 (number fractions: Schonberner 1975; Cottrell and Lambert 1982).

(4) From existing spectroscopic analyses and pulsational calculations, one can estimate a typical RCB mass of about 0.9 M⊙ (Saio and Wheeler 1985; Weiss 1987a,b; Saio and Jeffery 1988).

(5) They certainly belong to an old stellar population because their galactic distribution has a scale height of ≈ 500 pc (M(bol) = -5 assumed).

Despite the fact that the history of RCBs is still not well understood (cf. section 6 below), the use of stellar models with the appropriate composition and with reasonable masses has proven somewhat successful (cf. Weiss 1987a). In fact, some of the above listed properties were derived from such models. Starting from a (hypothetical) helium main sequence, a helium-star model of about 1 M⊙ evolves like a normal star, but with a larger luminosity, towards the Hayashi limit (lower branch). The model moves further upwards along the Hayashi line until contraction to the white-dwarf region sets in as the envelope mass falls below about 0.1 M⊙ (upper branch).

An important piece of information is provided by the pulsational properties of RCBs, although neither the periods nor the effective temperatures are well known in most cases. For the best known cases, RY Sgr and R CrB, it appears that only on the upper, high-luminosity branch does the blue edge of the instability region extend far enough to higher effective temperatures to explain the pulsations in these two

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objects (Weiss 1987b). The case of RY Sgr is in particular interesting since its period is the best known, P = 38.6 d, but decreases according to $\dot{P}/P \approx -3 \times 10^{-4}$ yr^{-1} (Pugach 1977; Maracco and Milesi 1982; Kilkenny and Flanagan 1983). This period decrease indicates evolution towards the blue with a (pulsational) time scale of 3000 years. A stellar model of Weiss (1987a, 1987b) which closely matches the spectroscopically determined parameters of RY Sgr predicts P = 37 d and $\dot{P}/P = -5 \times 10^{-4}$ yr^{-1}. This model has M = 0.88 M☉ and L = 18,000 L☉ and is on the upper evolutionary branch. We conclude that RY Sgr evolves like an appropriate stellar model in thermal equilibrium (i.e., L = L(He)) towards higher effective temperatures with constant luminosity.

In the following we will assume that indeed only the high-luminosity (i.e. upper) branch is realized in nature and check whether the observations are consistent with this assumption (see also the discussion in secction 6). The known periods of RCBs range from 38.6 d (RY Sgr) up to ≈ 135 d (S Aps)*. The coolest models of Weiss at about 4000 K predict fundamental periods of about 400 d, far above 135 d, which corresponds to ≈ 5000 K. Thus one may conclude that either very cool RCBs with, say T(eff) below 5000 K, do not exist or that they are hidden behind optically thick dust shells. Support for the latter idea comes from non-adiabatic pulsational calculations by Saio and Wheeler (1985), which indicated that for M < 1.6 M☉ and T(eff) < 6000 K the pulsational amplitudes grow without bound. In reality one has, therefore, to expect substantial mass ejections in all these cases. However, a better knowledge of effective tempertures and pulsational periods of RCBs is important to further investigate the relation between periods and stellar temperatures. For example, Kilkenny and Whittet (1984) estimated T(eff) = 4000 K for S Aps, a temperature which is incompatible with a period of 135 d.

*The fundamental mode seemed recently to have switched to the first overtone with ≈ 40 d, as reported by Kilkenny and Flanagan (1983).

As for R CrB itself, Gillett et al. (1986) detected by careful inspection of IRAS data a very cool (T(d) ≈ 30 K) and large (r(i) ≈ 0.7 pc) additional dust shell. With an expansion velocity of 20 km/s, this fossil dust shell is at least 30,000 yr old. Looking at appropriate models on the upper branch (Weiss 1987b, Table 7) one finds that the (contraction) time scale is about 40,000 yr at T(eff) = 4500 K, but only about 3000 yr at T(eff) = 7000 K (the present temperature of R CrB). Thus it appears that the fossil shell around R CrB was ejected when the star was much cooler, say T(eff) ≈ 4000 ... 5000 K. This interpretation would then be consistent with the above findings for RY Sgr. In this context it is interesting to note that fig. 1 of Walker (1985) clearly indicates very similar cool "fossil" shells around some other RCB stars. Because these cool shells appear to have some bearing on the evolutionary history of these objects, their thorough investigation is badly needed.

5. COMPARISON BETWEEN PROTO-PLANETARY NEBULAE AND R CORONA BOREALIS STARS

In this section we shall discuss similarities and dissimilarities between both groups of stars. Upon closer inspection of their properties it will become clear that they have little in common except that they both contain evolved stars with dusty circumstellar shells which populate similar regions in the H-R diagram. The typical properties are listed in Table 1.

Table 1: Typical properties of PPNs and RCBs

		PPNs	RCBs
envelope composition	:	normal	extremely hydrogen poor
stellar mass ($M_\odot$)	:	≈ 0.6	≈ 0.9
envelope mass ($M_\odot$)	:	$\lesssim 0.001$	$\lesssim 0.1$
temperature range (K)	:	5000 ... 10,000	5000 ... 7000 (16,000)*
dust temperature (K)	:	≈ 100	≈ 700
evolutionary rate (K/yr)	:	≈ 10	$\lesssim 1$
typical luminosity ($L_\odot$)	:	≈ 6500	$\approx 15,000$
core growth rate ($M_\odot$/yr)	:	$\approx 1 \times 10^{-7}$	$\approx 2 \times 10^{-6}$

* MV SGR (Jeffery et al. 1988)

Some comments seem to be in order. Firstly, the warm dust around RCBs indicates that their shells are closer to the stellar surface than is the case for PPNs. But this means only, of course, that the dust mass-loss rate is larger, and not necessarily the gas mass-loss rate! Note, for instance, that a RCB-like surface composition contains more refractory matter - namely carbon - than a solar-like composition. With a typical carbon-to-helium ratio as mentioned in section 4, one expects a gas-to-dust ratio of 10-100, the dust mainly being made out of amorphous or graphitic grains. This fact is important and should be considered when estimating total (i.e. dust plus gas) shell masses. For instance, solar-like compositions yield gas-to-dust ratios of about 250. Contrary to the PPNs, mass-loss rates for RCBs are not known. Feast (1986) estimates rates of about 10^{-6} $M_\odot$/yr, taking the peculiar photospheric composition into account and assuming that all carbon condenses. This rate is rather modest and can hardly compete with the burning rate (see Table 1). This would then explain why evolutionary calculations without mass loss correctly predict the observed

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evolutionary rates of RY Sgr (cf. section 4). Note that the PPNs have a burning rate lower by about a factor of ten, mainly due to the higher energy yield of hydrogen nuclear fuel, making their post-AGB evolution more dependent on the mass-loss rates.

Furthermore, the rather slow contraction of RCBs compared to PPNs explains the non-existence of helium-dominated planetaries. The total transition time from the Hayashi limit to the planetary-nebula region obviously exceeds the kinematical lifetime of any circumstellar shell. The so-called Wolf-Rayet central stars, which are believed to have hydrogen-free surfaces, possess nebular shells with solar composition. By contrast the RCBs will most likely turn into the so-called extremely hydrogen-deficient helium stars, none of which is known to possess a planetary, before they descend to the subdwarf and white-dwarf region (cf. Schonberner 1986).

6. COMMENTS ON THE ORIGIN OF R CORONA BOREALIS STARS

A detailed account about our understanding of the origin of RCBs has already been given elsewhere (Schonberner 1986); thus, only a few but nevertheless important points shall be emphasized again. There are two facts that exclude the possibilty that the RCBs are direct descendants of the AGB, contrary to earlier opinions. First of all, the evolutionary models (Schonberner 1977; Weiss 1987a) predict helium-envelope masses of the order of 0.1 $M_\odot$, which exceed the helium intershell mass in AGB stars with a comparable core mass by factors of 10 (cf. Paczynski 1975)! Secondly, deep envelope burning on the AGB, which would convert all the hydrogen into helium (Scalo et al. 1975), does not operate since the envelope composition of RCBs indicate a mixture of CNO-processed with triple-alpha-processed matter. The only hypothesis which seems to give at least a qualitative explanation for the existence of RCBs is that proposed by Webbink (1984) and further discussed by Iben and Tutukov (1985); namely, the merger of two close binary white dwarfs, one with a carbon-oxygen core, the other with a helium core. For more details, the reader is referred to the original papers cited above, or to Schonberner (1986).

It shall explicitly be emphasized here that the so-called "late-flash" scenario proposed by Iben et al. (1983) cannot explain the observed evolutionary lifetimes of RY Sgr and R CrB. Such a model is completely out of thermal equilibrium and has an evolutionary time scale in the vicinity of the AGB of about 100 year, as opposed to the observations which indicate time scales of several 1000 years for these two stars (cf. discussion of section 4). We think that this scenario, though it might be responsible for some exotic objects, will not work for the majority of RCBs.

Not much is known about the evolutionary status of a class of peculiar supergiants not mentioned at all in this review; viz., the extremely hydrogen-deficient carbon stars. Their spectra are very similar to those of RCB stars, yet they do not seem to possess any circumstellar dust shells (Feast and Glass 1973; Drilling et al. 1984; Walker 1985). Also, they do not pulsate, although Kilkenny (1988) seems to have detected low-amplitude, semi-regular variations in some cases. These may represent an extension of the RCB group to lower masses, and hence also to lower luminosity-to-mass ratios (Schönberner 1986).

In concluding this section, it must be stated that we are still far from an understanding of the origin of RCB stars.

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