EVOLUTIONARY EFFECTS OF MASS LOSS IN LOW-MASS STARS

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ABSTRACT

The effects of mass loss on the evolution of low-mass stars (actual mass smaller than 1.4 $M_\odot$) are reviewed. The case of globular cluster stars is discussed in some detail, and it is shown that evolutionary theory sets quite precise limits to the mass-loss rate in population II red giants. The effects of mass loss on the final evolutionary stages of stars producing white dwarfs is also discussed. In particular, the interaction of the wind from the hot central star with the surrounding planetary nebula is considered. Finally, the problem of the origin of hydrogen-deficient stars is briefly discussed.

1. INTRODUCTION: SOME METHODOLOGICAL CONSIDERATIONS

In this paper by "low-mass stars" one intends: i) very old stars, like those in galactic globular clusters, and ii) stars having completed their asymptotic giant-branch (AGB) evolution, and evolving towards their final white-dwarf configuration. Stars in the first group have initial masses less than about 0.9 $M_\odot$, while those in the second group have masses less than 1.4 $M_\odot$ (the Chandrasekhar limit) but represent the progeny of considerably more massive stars, having lost most of their envelope during the AGB phase. Stars in the latter group are also called post-AGB stars.

Mass loss can affect in various ways the evolution of low-mass stars, and one may argue that the most rigorous methodological approach should consist in two steps: i) derive from observations the mass-loss rate (MLR) for a variety of stellar types, and ii) incorporate this MLR into the calculation of evolutionary sequences, and in such a way predict the

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evolutionary effects of mass loss. However, the current empirical estimates of the MLR are so uncertain that this approach would not give any precise prediction, i.e. the "rigorous" method does not produce astrophysically relevant results. This means that either one has to wait for a substantial improvement of the current mass-loss diagnostics, or to follow another method. Since the wait has been already rather long, I personally prefer the second choice. One has also to mention that there is not yet a general consensus about the physics of the mass-loss process itself, i.e. about the mechanism(s) responsible for the acceleration of matter in the outer parts of stellar atmospheres. The least one can say about extant wind models is that they are rather crude. In other words, the theory of winds is unable to derive reliable MLR's from first principles, and the "observed" MLR's are too uncertain. This being the present situation, it should appear clear the importance of deriving better MLR's using other tools.

In this paper I will try to show that the theory of stellar evolution can be a valuable tool. In fact, it happens that the advanced evolutionary phases of low- and intermediate-mass stars are crucially dependent on the efficiency of the mass-loss processes, in particular of those operating in red-giant stars. The method one intends to apply can be called "parametric method", as it consists of i) a parametrization of the MLR, ii) the calculation of evolutionary sequences incorporating the parametrized MLR, and iii) the determination of the MLR parameter(s), which is achieved by demanding to the evolutionary sequences to fulfil various astrophysical constraints (e.g. the reproduction of observed color-magnitude diagrams, and many others). Therefore, the final product of this approach is the determination of the MLR, and a consistent description of the advanced stages of stellar evolution. Obviously, the MLR determined in this way is entirely dependent on the reliability of theoretical evolutionary calculations. This reliability can be checked controlling how many observational constraints are actually fulfilled by the models.

By parametrized MLR one intends an expression relating the MLR to the various stellar parameters (in particular the stellar mass, radius, luminosity, and composition). It is conceivable that the MLR could also depend on other physical quantities (like stellar rotation, strength and structure of magnetic fields, etc.). However, a parametric method is most reliable when the number of "free" parameters is very low compared to the number of observables to be fitted. For this reason, in the first approach it is preferable to limit to a minimum the number of parameters, leaving the complications to a second step, if the first approach would

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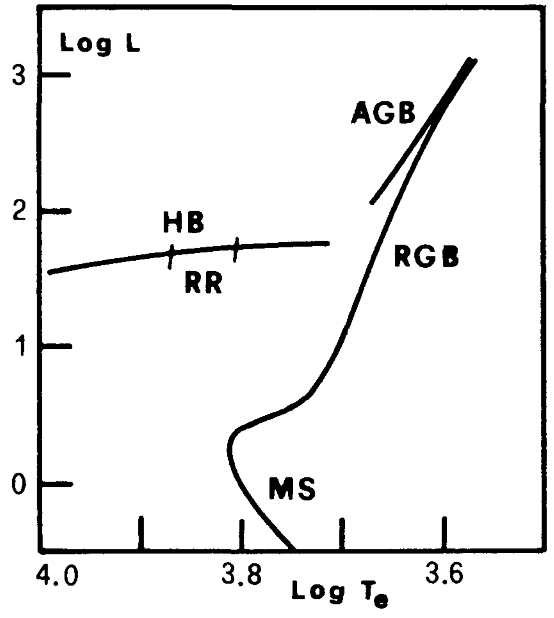

Figure 1. The schematic HR diagram of a typical globular cluster of intermediate metallicity (e.g. M3). The main branches are identified.

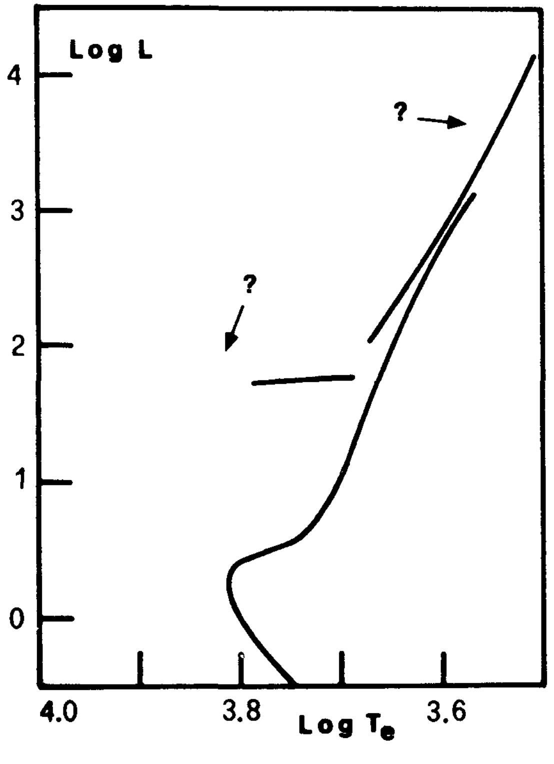

Figure 2. The theoretical HR diagram, computed neglecting mass loss. The HB and AGB discrepancies are indicated.

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fail in some important aspect of the problem.

The so-called Reimers parametrization is frequently used for the MLR due to the wind in the red-giant phases (Reimers, 1975, 1981), i.e. one assumes:

$$\dot{M} = -4\ 10^{-13}\ \eta L/gR \qquad (M_\odot/yr) \qquad (1)$$

where the luminosity L, the surface gravity g, and the radius R are in solar units, and where η represents the mass-loss parameter. No attempt will be made here to justify this particular choice for the MLR expression, other choices could be similarly legitimate, and their implications could be tested using exactly the same procedures.

2. POPULATION II STARS

Figure 1 shows the schematic HR diagram of a typical globular cluster of intermediate metallicity (e.g. the cluster M3). The main characteristics of this diagram are: a) the horizontal branch (HB) is about 3.4 mag brighter than the main-sequence turnoff, b) the HB is fairly extended in effective temperature, containing stars at both sides of the RR-Lyrae region, and c) the AGB approaches the red-giant branch (RGB) without exceding in luminosity the termination of the RGB.

When evolutionary sequences are computed under the assumption of mass conservation ($\dot{M}$ = 0) one obtains the diagram shown in Figure 2, where condition a) has been imposed (cf. Renzini, 1977, and the literature quoted therein). A comparison between the theoretical and the observational diagrams reveals that: i) the RGB luminosity function is in excellent agreement with the observations, in particular the termination of the theoretical RGB agrees to better than $0^m.25$ with the luminosity of the RGB tip (cf. Frogel, 1981, for a recent account); ii) contrary to the observations, the calculated HB is populated only on the red side of the RR-Lyrae region (no blue HB nor RR-Lyrae stars are produced); iii) the theoretical AGB extends $\sim 2^m.5$ above the RGB tip, and this is at variance with the observations. Therefore, the question arises on how to remove the HB and AGB discrepancies *without destroying* the RGB agreement.

2.1 The HB discrepancy

Back in the late sixties (Castellani and Renzini, 1968; Iben and

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Rood, 1970) it was realized that a substantial mass loss ($\sim$0.2 $M_\odot$) during the RGB phase would remove the HB discrepancy. When condition a) is imposed the initial mass of evolving stars turns out to be $\sim$0.85 $M_\odot$, and, correspondingly, the typical mass of HB stars is $\sim$0.65 $M_\odot$. It is worth emphasizing that this determination of the mass of HB stars is i) entirely based on evolutionary models (i.e. it is an *evolutionary* mass), and ii) it agrees with the *pulsational* mass obtained using the pulsation theory for RR-Lyrae stars (cf. Christy, 1966; Iben, 1971).

Nearly in the same period, it became also clear that single HB evolutionary sequences did not reproduce the observed temperature range covered by HB stars in one cluster, i.e. the theoretical HB sequences were systematically *too short* compared to the observed HB's. This discrepancy could be removed by assuming that HB stars in one cluster follow slightly different evolutionary lines, as the result of some *individuality* distinguishing one star from another. Among other possibilities, a range in mass or/and in core mass among HB stars in one cluster would produce the desired effect (Castellani *et al.* 1969, Iben and Rood, 1970). In practice, Rood (1973) found that a dispersion $\sigma(M_{HB}) \simeq 0.025$ $M_\odot$ is required to reproduce the observations. Independently of purely evolutionary considerations, Castellani *et al.* (1970) showed that the properties of RR-Lyrae stars also demand a certain amount of dispersion in at least one parameter among HB stars in one cluster. Once again, evolution and pulsation theories pointed in the same direction.

Using the parametric method (Fusi-Pecci and Renzini, 1976; Renzini, 1977) it is possible to obtain the value of η (cf. Eq. 1) leading to M_{HB} = 0.65 $M_\odot$, in agreement with the requirement discussed above. Figure 3 shows various theoretical HB's, obtained with different values of η, and under the assumption that *individuality* is represented by the initial stellar rotation (for more details cf. Renzini, 1977). Figure 3 shows that the morphology and the location of the HB is extremely sensitive to the adopted value of η. This is entirely a consequence of the fact that the effective temperature of HB stars is very sensitive to both the total mass and the core mass. More precisely, the case η = 0.40 provides a rather evenly populated HB, with nearly the same number of blue and red HB stars, and many RR-Lyrae stars (like in the cluster M3). When η is reduced by 10% (η = 0.36) most stars lie to the red of the RR-Lyrae instability strip, there are fewer RR-Lyrae and very few blue HB stars. When η is increased by 10% (η = 0.44) most stars lie to the blue of the instability strip, only few stars remain within the instability strip, and the red HB stars have almost completely disappeared. We can conclude that, for this choice of the cluster parameters (age and composition), the HB morphology of M3 is reproduced by adopting $\eta = 0.40 \pm 0.04$, where the uncertainty is rather generously estimated. Furthermore, using the analytic algorithms given by Renzini (1977), it is not difficult to conclude that for $\eta > \sim 0.6$ (the actual value would depend on composition) the HB and AGB phases would be completely suppressed. In fact, with such large MLR the whole hydrogen-rich envelope would be lost along the RGB before the core mass reaches the critical value ($\sim 0.5\ M_\odot$) for the helium ignition. Correspondingly, the star would leave the RGB becomig a white dwarf, and skipping the HB and AGB phases. In this way a very stringent upper limit to η is established.

It is worth mentioning that the value of η derived with the HB fitting is somewhat sensitive to the estimated cluster age, which, in turn, is uncertain by a few billion years (cf. Renzini, 1977). On the other hand, the derived value of η does not depend on the assumed cluster helium abundance, provided that condition a) is imposed (Renzini, 1977). Furthermore, uncertainties in the cluster metal abuncance, and in the

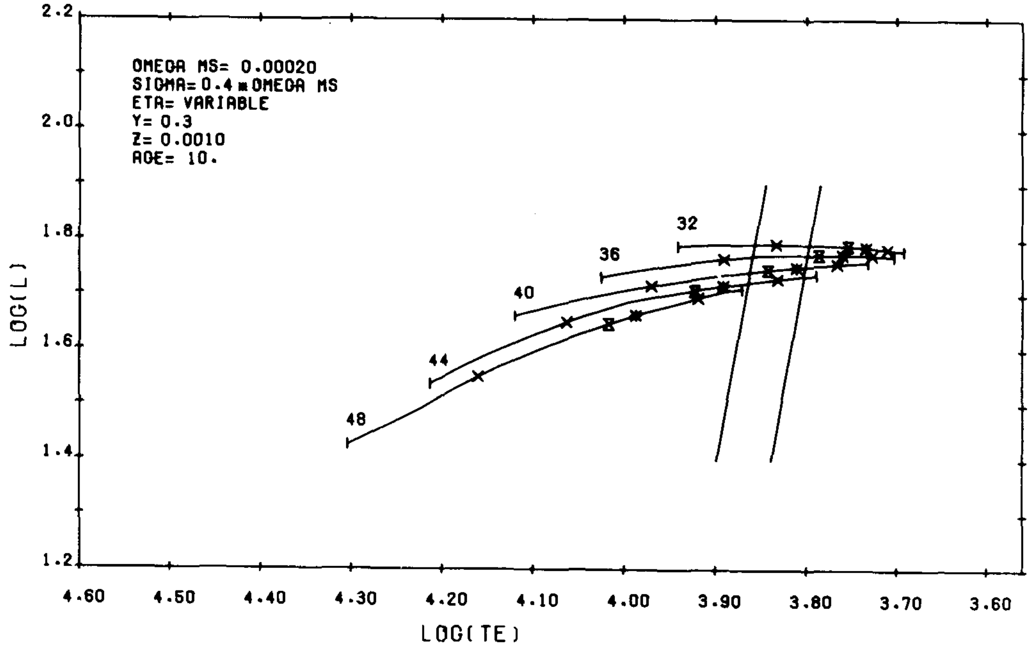

Figure 3. Various HB loci are shown for different values of the parameter η. Each HB is labelled by the value of η multiplied by 100. Age, composition, and rotational parameters are indicated (cf. Renzini, 1977). The diamonds mark the middle of the distributions.

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relation between effective temperature and luminosity for red-giant stars, generate some additional uncertainty in the derived value of η. When all these effects are properly taken into account one can estimate that the overall uncertainty affecting η is of the order of 20-30%. This uncertainty is by far much smaller than the error affecting any empirical determination of the MLR.

2.2 The AGB discrepancy

AGB stars burn hydrogen and helium in two separate shells, and their luminosity increases with increasing mass of the hydrogen-exhausted core. Clearly, the luminosity does not cease to increase unless a further progression of the hydrogen-burning shell is prevented in some way. The latter condition is verified only for vanishing mass of the hydrogen-rich envelope. Correspondingly, mass loss, reducing the mass of the envelope, will affect the maximum luminosity reached by AGB stars: the larger the assumed MLR, the fainter the AGB termination. The value of η required to remove the AGB discrepancy can be inferred by i) using the AGB evolutionary rate given by Gingold (1974), ii) setting the stellar mass at the beginning of the AGB phase equal to M_{HB}, and iii) imposing the condition that the termination of the AGB has approximately the same luminosity of the RGB tip. This value turns out to be $\sim$0.40, in excellent agreement with the value required to remove the HB discrepancy.

Therefore, we can reasonably conclude that both the HB and AGB discrepancies were due to the omission of the mass-loss effects in model calculations, and that the same value of the mass-loss parameter η ($\sim$0.4) allows to eliminate both discrepancies. This means that the strength of the wind is basically the same on both red-giant branches. Finally, one has to mention that the introduction of mass loss does not affect appreciably the RGB properties (luminosity function, etc.), and therefore the RGB agreement is not destroyed.

2.3 The Z-dependence of the mass-loss rate

The HB morphology is very sensitive to the metal abundance Z, and the question arises whether we can legitimately use the same value of η for clusters with different metallicity. Among galactic globular clusters Z ranges from $\sim 10^{-4}$ to $\sim 10^{-2}$ (cf. Zinn, 1980), but unfortunately we have no observational indication whatsoever about the variation with Z of the MLR, i.e. about $\dot{M}(Z)$. This limitation tends to prevent a *global* understanding of the various HB morphologies exhibited by globular clusters, and makes more difficult the identification of the so-called "second parameter" (cf. Renzini, 1977). However, if our ignorance of the

Z-dependence of the MLR complicates the life of those attempting the reproduction of observed HB morphologies, on the other way around, from the latter ones one can infer something about $\dot{M}(Z)$.

As a rule, the HB of metal-poor clusters is essentially blue, with few RR-Lyrae stars. The intermediate metal-poor clusters have an evenly populated HB, and the metal-rich clusters have a red HB. (The clusters which do not follow this trend are those suggesting the existence of the "second parameter".) The fact that metal-poor clusters have a blue HB sets a *lower* limit to the amount of mass (ΔM) which can be lost along their RGB: for $\Delta M < 0.1\ M_\odot$ metal-poor clusters would have a *red* HB, and this contradicts the observations. Analogously, the fact that metal-rich clusters have a red HB sets an *upper* limit to their ΔM: for $\Delta M > 0.3\ M_\odot$ these clusters would have a *blue* HB. One can conclude that the MLR in population II red giants cannot vary by more than a factor of 3, while Z changes by two orders of magnitude. This means that the MLR has to be almost insensitive to the metal abundance, and, correspondingly, this sets a strong constraint to theories of the wind process in this type of red giants.

While the main ideas discussed so far were basically accepted already ten years ago by all model makers, the first direct obsevational evidence of mass loss from population II giants did not appear until 1976, when Cohen (1976) discovered Hα emission wings in the spectra of a few bright RGB stars in globular clusters. Successively, Mallia and Pagel (1978) reported similar results, and more recently Cacciari and Freeman (1981) have completed a fairly extended survey, obtaining spectra of about 150 red giants in various globular clusters. The main results of their study are that the Hα emission is i) variable in time, and ii) confined to stars on the upper RGB (or AGB). In practice, only stars lying within about one magnitude from the RGB tip do show the Hα emission. This is in *qualitative* agreement with Eq. (1), which predicts relatively high MLR's only for bright RGB (or AGB) stars. This circumstance was already pointet out by Bond (1978) for a sample of population II red giants in the field. However, to push this comparison forward, more sophisticated diagnostic tools should be developed.

3. POST-AGB STARS

The AGB evolution of intermediate-mass stars ($\sim 1 < M < \sim 8\ M_\odot$) is crucially affected by mass loss; in particular, assumptions about the mass-loss processes acting on the AGB have immediate consequences for:

i) the final product of stellar evolution (i.e. a white dwarf or a supernova),
ii) the type and amount of ejected nucleosynthetic products,
iii) the type and amount of ejected dust grains,
iv) the maximum luminosity reached along the AGB,
v) the production and properties of carbon stars,
vi) the production and properties of Mira variables,
vii) the production of planetary nebulae (PN),
viii) the mass and composition of PNe,
ix) the mass spectrum of PN nuclei and white dwarfs.

These topics have been investigated and/or reviewed in a number of papers (e.g. Fusi-Pecci and Renzini, 1976; Wood and Cahn, 1977; Renzini, 1977, 1979, 1980, 1981; Weidemann, 1977; Iben and Truran, 1978; Becker and Iben, 1980; Renzini and Voli, 1981; Iben, 1981; Schönberner and Weidemann, 1981; Wood, 1981), and at this meeting are discussed by Iben, Weidemann and Willson. In particular, Renzini (1981) has revived the arguments indicating that at least two mass-loss processes must operate in AGB stars, namely: a *regular* wind approximated by the Reimers MLR (cf. Eq. 1), with $\dot{M}$ ranging from a few 10^{-8} to a few 10^{-6} $M_{\odot}/yr$, followed by a phase of more drastic mass loss, but whose duration is short compared to the evolutionary time. The latter process has been provisionally called *superwind*, and its nature is still controversial. Some researchers think that the superwind is triggered by the violent envelope pulsation in the fundamental mode, following the pulsation in the first harmonic, which is believed to be the pulsational mode of Mira variables (e.g. Wood and Cahn, 1977; Tuchman *et al.* 1979; Wood, 1981). Others prefer to regard Miras as pulsating in the fundamental, and in this case the superwind would be produced by the wind-pulsation interaction (e.g. Willson, this volume). Apart from the quest of the pulsational mode of the Miras, these different points of view are uninfluential on a parametrized treatment of the AGB evolution (Iben and Truran, 1978; Renzini and Voli, 1981), the main question being the relative contribution of the wind and the superwind to the total mass reduction during the AGB phase. In attempting the determination of these relative contributions one must consider *all* the astrophysical constraints implied by the nine topics listed above. In fact, owing to the current observational and theoretical uncertainties, it would be extremely dangerous to draw sharp conclusions having considered just one aspect of this intricated problem.

During the superwind phase the envelope mass is rapidly decreasing, and when it reaches a critical value the stellar model starts moving away from the AGB. When the mass of the residual envelope drops below another critical value (M_R^e) the superwind is quenched and the normal red-giant wind resumes. We can conventionally take this instant as the beginning of the post-AGB phase. The actual value of M_R^e must depend on the core mass and composition, but it is extremely difficult to derive it on theoretical grounds. Combined evolutionary and hydrodynamical calculations would be required, but particularly the latter ones are extremely uncertain. The only attempt in this direction has been tried by Härm and Scharzschild (1975), and these numerical experiments are of fundamental importance for the understanding of the process leading to the formation of PNe. In fact, as recently discussed by Renzini (1981), the actual value of M_R^e directly controls even the *possibility* of forming PNe. In order to have an *order of magnitude* estimate of M_R^e one can assume that it is comparable to the envelope mass when the AGB star departs from the Hayashi track. In this case one can estimate $M_R^e \simeq 0.005\ M_\odot$ for $M_c = 0.6\ M_\odot$, and $M_R^e \simeq 0.01\ M_\odot$ for $M_c = 1.2\ M_\odot$, M_c being the mass of the hydrogen-exhausted core (cf. Gingold, 1974; Paczynski, 1971).

3.1. The quiescent evolution of post-AGB stars

After the superwind phase has ceased stars evolve to the blue at almost constant luminosity, reach a maximum effective temperature in excess of 10^5 K (the actual value depends on M_c), and eventually start fading approaching a R = const. line, i.e. a white-dwarf cooling sequence. The luminosity of the horizontal part of the track is well approximated by the Paczynski relation:

$$L = 59200\ M_c - 30950 \qquad (L_\odot) \tag{2}$$

which holds for AGB stars (Paczynski, 1970). The maximum effective temperature along the sequence is $\log T_e \simeq 5.2$ for $M_c = 0.6\ M_\odot$, and $\simeq 5.84$ for $M_c = 1.2\ M_\odot$ (Paczynski, 1971).

For each value of M_c, there is a one to one correspondence between the residual envelope mass and the location of the model on the evolutionary track: i.e. the evolution is primarily driven by the decrease of the envelope mass. Two processes cooperate in reducing the envelope mass, namely: nuclear burning in the hydrogen-burning shell, and mass loss by stellar wind, i.e.

$$\dot{M}^e = -\dot{M}_c + \dot{M} \simeq -(L/E_H X^e) + \dot{M} \tag{3}$$

where E_H (= 6 10^{18} erg) is the energy released by the conversion of 1g of hydrogen into hemium, and X^e is the hydrogen abundance in the envelope. For post-AGB stars which are still on the horizontal part of the track one can use Eq. (2) and one gets:

$$\dot{M}_c \simeq 6\ 10^{-7} (M_c - 0.44) \qquad (M_\odot/yr) \qquad (4)$$

which gives $\dot{M}_c = 6\ 10^{-8}\ M_\odot/yr$ for $M_c = 0.54\ M_\odot$, and $\dot{M}_c = 6\ 10^{-7}\ M_\odot/yr$ for $M_c = 1.4\ M_\odot$. Clearly, depending on the relative values of $\dot{M}_c$ and $\dot{M}$, the post-AGB evolution will be dominated by shell burning ($\dot{M}_c >> -\dot{M}$), or by mass loss (when $\dot{M}_c <\sim -\dot{M}$). Post-AGB evolutionary sequences including mass loss have never been computed so far, and it would be very important to have a fairly extended grid of post-AGB sequences for various values of M_c and M_R^e, and for various assumptions concerning the MLR.

For some time after the superwind has ceased the star remain a red giant, and a Reimers-like wind is probably appropriate. Then the star moves quite rapidly to the blue, and its spectral type evolves through the K, G, F, A, and B types. The MLR in supergiants of these spectral types is very poorly known. However, the transition from K to B is rather fast even neglecting mass loss (cf Paczynski, 1971), and this uncertainty should not cause much trouble.

When the star enters the region of PN nuclei its atmosphere is not much different from that of upper main-sequence stars (at least as far as gravity and temperature are concerned). These stars are known to support a fast wind, and it was quite reasonable to speculate that also PN nuclei do the same (cf. Paczynski, 1978; Renzini, 1979). In fact, it is known from a long time that several PN nuclei have spectral types like Of or even WR (cf. Smith and Aller, 1969; Aller, 1976; Lutz, 1978). Actually, recent IUE observations of PN nuclei have completely confirmed this expectation, but the problem of the MLR remains. In a recent review by Nussbaumer (1980) MLR's from less than $10^{-10}\ M_\odot/yr$ to $\sim 10^{-7}\ M_\odot/yr$ are reported. Benvenuti and Perinotto (1980) give MLR's ranging from $\sim 10^{-11}$ to a few $10^{-9}\ M_\odot/yr$ in a sample of five PN nuclei. Castor *et al.* (1980) give $10^{-7}\ M_\odot/yr$ for the central star of NGC 6543, while Heap (1980) reports $10^{-6}\ M_\odot/yr$ for the same object. Pottasch (1980) gives an average MLR of $\sim 10^{-10}\ M_\odot/yr$ for a number of central stars. These figures must be compared with the values given above in order to figure out whether mass loss is an important factor in the evolution of PN Nuclei, and in particular for the PN lifetimes. It appears that NGC 6543 is so far the only case in which mass loss may be important.

It is worth warning that solar abundances of the CNO elements should *not* be used in determining the MLR of PN nuclei (cf. Renzini, 1981), the nebular abundances should be more appropriate, if available. It is also important to stress that the mass of the central star (and its location on the HR diagram!) should be known before inferring the evolutionary relevance of the observed MLR.

Complementary considerations on the evolution of post-AGB stars are developed in other papers (Renzini, 1979, 1981). The possible effects of mass loss during the thermal runaway caused by helium-shell flashes will be discussed in section 3.3.

3.2. The wind-nebula interactions

From the previous discussion it emerges that the central stars of PNe are surrounded by at least four gaseous components, namely: i) the fast wind emanating from the central star and running at a typical velocity of about 1000 km/s, ii) the remnant of the AGB superwind (typical expansion velocity 20 km/s), iii) the remnant of the AGB regular wind (typical expansion velocity 10 km/s), and finally iv) the ISM, supposed at rest. Owing to the dynamical interactions among these components, shocks may develop producing even more complicated thermal and kinematical structures. Furthermore, the UV flux from the central star will ionize part of the surrounding materials, and another shock may develop at the interface between ionized and neutral gas, and Rayleigh-Taylor instabilities may arise at the various interfaces. If one considers that a) this complicated machine evolves with time, and b) the mass and velocity of the various components are presumably rather sensitive to the initial mass of the parent star, it is rather clear that an enormous variety of instantaneous configurations is possible. Even more complicated structures could be originated if a PN has been ejected by a member of a binary system.

Models of the evolution of PNe should include the various components, establish their relative importance, take into account the evolution of the central star, and consider the variety of possible initial conditions (in particular the fact that PNe are presumably produced by stars in a rather wide range of initial masses).

In the scheme proposed by Renzini and Voli (1981) stars with an initial mass $\sim 0.85\ M_\odot$ leave a remnant of $\sim 0.54\ M_\odot$, and the superwind phase ejects about 0.02 $M_\odot$. The material ejected in the superwind mode is expected to produce the PN, once it is excited by the UV photons emitted by the central star. Correspondingly, the momentum of the nebula is $\sim 0.02 \times 20 = 0.4\ M_\odot$km/s. When the central star reaches high temperatures its hydrogen-rich envelope has a mass of $\sim 0.001\ M_\odot$ (Paczynski, 1971). Supposing that most of this envelope is ejected by the fast wind with a velocity of ~ 1000 km/s, the overall momentum imparted to the nabula by the fast wind is $\sim 1\ M_\odot$km/s. That is, the fast wind may influence the dynamical evolution of the nebula. In particular, the fast wind could prevent the so-called *back-filling* effect, as originally suggested by Mathews (1966) in order to account for the ring shape of so many PNe. It could also be important during the early evolutionary phases of the nebula, as suggested by Kwok *et al.* (1978) and Kwok (1981).

However, in the frame of the same scheme, stars with an initial mass of 4 $M_\odot$ leave a remnant of $\sim$1.3 $M_\odot$, and the mass lost during the superwind phase is $\sim$1 $M_\odot$. Correspondingly, the momentum of the nebula is $\sim$ 20 $M_\odot$km/s. In this case the mass of the hydrogen-rich envelope is only $\sim 10^{-5}$ $M_\odot$ (Paczynski, 1971) and the fast wind can provide a momentum of (at most) 0.01 $M_\odot$km/s, i.e. the momentum of the wind is about 2000 times smaller than the momentum of the nebula. Correspondingly, the effects on the morphology and evolution of the nebula are negligible.

These examples illustrate how dramatic can be the variations of the nebular characteristics depending on the mass of the parent star. Low-mass progenitors will likely produce ring-shaped nebulae, with a sharply-bounded inner hole, while higher-mass progenitors should produce rather homogeneous nebulae, without central hole. In this connection, it is worth noting that high-mass progenitors are expected to produce PNe with low-luminosity central stars (Renzini, 1979, 1981). Abell's planetaries, having very faint nuclei (O'Dell, 1963), are very likely the product of rather massive progenitors. If the above considerations are correct, most Abell's PNe should appear centrally filled, and a cursory examination of the catalogue of Perek and Kohoutek (1967) reveals that this is actually the case (Perinotto, 1980).

Extended halos of low surface brightness have been observed around many PNe (e.g. Millikan, 1974), and they are interpreted as evidence of the remnant red-giant wind (e.g. Fusi-Pecci and Renzini, 1976; Kwok, 1981). The observation of dust-scattered light and CO emission around NGC 7027 (Condal *et al.* 1979; Mufson *et al.* 1975) provides additional evidence for the presence of a remnant red-giant wind (Kwok, 1981). It would be of great value to extend these observations to many other PNe, as they could give useful information on the relative mass of the regular red-giant wind and the superwind.

3.3. Origin of hydrogen-deficient stars

In a (log g - log T_e)-diagram, theoretical post-AGB evolutionary lines stream from the AGB to the WD cooling sequences. In the same diagram, a variety of *strange* stars are located in the region bounded by the post-AGB sequences, suggesting the possibility of an evolutionary

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connection between strange stars and post-AGB stars. Strange stars share the common property of being extremely deficient in hydrogen. Actually, in most cases, it is not clear whether they have any hydrogen at all. These stars are classified in three main classes, namely: i) hydrogen-deficient carbon stars (HdC), which following Warner (1967) include three sub-types: a) the R Cr B stars, characterized by prominent carbon features, $T_e \simeq 6000$ K, and by the typical luminosity variations, b) the cool HdC stars, similar to R Cr B stars but apparently non variable, and c) the extreme helium stars, with T_e around 16000 K and rather carbon-rich, e.g. BD+10°2179 (Schönberner and Wolf, 1974); ii) nuclei of PNe with WR spectral type (all, but one dubious case, are of the type WC); and iii) non-DA white dwarfs. Other peculiar stars, like hydrogen-deficient SdO's, could be related to some of these classes.

Although the chemical analysis of these stars is extremely complicated by their peculiar composition, it appears that the atmospheres of stars in the first two classes are essentially composed of helium and carbon, with these two elements contributing about 98% by mass, and carbon alone some 10% or even more. It is important to emphasize that ^{13}C isotopic features are absent in cool stars (where, in case, they should be observable). The atmospheric composition of non-DA white dwarfs can be affected by diffusion processes. Nevertheless, it appears that hydrogen is extremely deficient (or totally absent), helium is the main contituent, and carbon is probably a major component in the so-called λ4670 stars (cf. Weidemann, 1975).

The chemical structure of post-AGB stars is essentially the following: i) a degenerate C-O core, containing most of the stellar mass, and where H, He, ^{13}C, and N are totally absent, ii) an *intershell* region whose mass depends on the total stellar mass (it decreases from $\sim$0.02 $M_\odot$ for M = 0.6 $M_\odot$ down to $\sim 2\ 10^{-5}$ $M_\odot$ for M = 1.4 $M_\odot$), and iii) a hydrogen-rich envelope, whose mass is continuously decreasing from $\sim 10^{-3}$-10^{-2} $M_\odot$ at the beginning of the post-AGB phase, down to less than $\sim 10^{-10}$ $M_\odot$ when stars become WD's. The chemical structure of the intershell depends on the phase of the helium-shell flash cycle. Just before a helium-shell flash the intershell consists of two layers, with the inner one containing about 2/3 of the intershell mass, and where helium is $\sim$80% by mass and carbon $\sim$20%, the precise values depending somewhat on the stellar mass (cf. Renzini and Voli, 1981, fore more details). In this inner portion of the intershell ^{13}C and N are totally absent, but there is some ^{16}O. The outer part of the intershell consists mostly of helium ($\sim$98%) and ^{14}N ($\sim$1%) while ^{12}C, ^{13}C, and ^{16}O are totally absent. Just *after* a helium-shell flash the inner part extends outwards in mass, and the outer part virtually disappears, i.e. past the flash the composition of the whole intershell is practically the same of its inner part before the flash.

It is clear that the composition of the intershell closely mimics that of the atmospheres of strange stars, and that, besides these post-AGB models, in no other realistic stellar models computed so far materials with this composition get so close (in mass) to the stellar surface. Therefore, it is rather tantalizing to speculate that (some) post-AGB stars could lose the remaining H-rich envelope, expose the intershell region, and then become strange stars. After all, the envelope mass of post-AGB stars is very small, and these stars are still losing mass. However, it is not so easy for post-AGB stars to get rid of their residual H-rich envelope. In fact, as mentioned in section 3.1, the main effect of mass loss during the quiescent post-AGB phase is to accelerate the evolutionary rate along the post-AGB sequence, i.e. for vanishing envelope mass the star would be already a white dwarf. But some strange stars are actually giants! Having excluded the quiescent phase, Renzini (1979) suggested that the complete envelope removal could take place during an *active* phase, following a helium-shell flash. However, as pointed out by Schönberner (1979), the situation is not much more favourable even in this case. In particular, the energy released by a helium-shell flash is insufficient to expand the intershell region to the large radius typical of some HdC stars, and the puzzle remains.

However, helium-shell flashes can provide the key to understand the origin of strange stars. In fact, as shown by Fujimoto (1977) and Schönberner (1979), if the final helium-shell flash takes place when the envelope mass is smaller than $\sim 10^{-5}$ $M_{\odot}$, the intershell convection can penetrate through the He-H discontinuity. When this happens, the residual envelope can be captured by the intershell region. For larger envelope masses, in particular in AGB stars, this event is impeded by the large entropy barrier between the intershell and the envelope. Once the envelope is mixed with the intershell, the captured protons are rapidly destroyed by the reactions $^{12}C(p,\gamma)^{13}N(e^{+}\nu)^{13}C(\alpha,n)^{16}O$, the residual envelope is suddenly burned, and for each ingested proton one neutron is produced. The released neutrons are rapidly captured to form s-process elements.

It is worth warning that it would be extremely difficult to compute evolutionary models under such circumstances, mainly because the lifetime of the protons is comparable to the characteristic time of convection, and a time-dependent convection theory should be used. Furthermore, low-temperature opacity tables for helium-carbon mixtures are not presently available. Nevertheless, one can reasonably conjecture that the thermonuclear runaway produced by the envelope burning could force the upper parts of the intershell to expand to large radii. Actually, depending on the mass of the captured envelope (which for *each* stellar mass can have any value between $\sim 10^{-8}$ to $\sim 10^{-5}$ $M_{\odot}$) a maximum radius can be reached. In this way, R Cr B stars could be produced, or, for lower captured masses, just smaller strange stars, like extreme helium stars or PN nuclei of WC type. In any case, the final product would be a non-DA WD, while R Cr B stars would reach this final stage after a passage through all other classes of strange stars. This process for the production of strange stars implies a lifetime of R Cr B stars of $\sim$1000 yr, if the stellar mass is about 0.6 $M_{\odot}$, although not all stars should necessarily experience these adventures. Somewhat longer lifetimes are more likely for smaller and fainter strange stars. It is worth emphasizing that the large range in the mass of the captured envelope will immediately translate into a correspondingly large range in the number of neutrons per iron-seed nucleous. Therefore, the abundance of s-process elements is expected to fluctuate enormously from star to star.

The case of the R Cr B star U Aqr, recently studied by Bond *et al.* (1979), may show the signature that this process took actually place. In fact, this star shows a large enhancement of the s-process elements Strontium and Yttrium.

Finally, the case of the peculiar PN A30 deserves a few comments. Hazard *et al.* (1980) have obtained spectra of three compact nebulosities around the central star of this extended PN. The remarkable feature of these nebulosities is that they are virtually hydrogen-free, as probably is the atmosphere of the central star, which appears to support a fast wind (Greenstein and Minkowski, 1964). The nebulosities clearly represent material recently ejected by the central star, but unfortunately Hazard *et al.* do not give their radial velocity. If this will turn out to be of the order of $\sim$1000 km/s, the nebulosities should have been ejected very recently, when the central star was not much different from its present appearance. However, if the velocity of the hydrogen-free knots is of the order of 100 km/s or less, they can possibly represent the remnants of asymmetric mass ejections during a previous R Cr B phase, i.e. the remnants of the famous *puffs* thought to be responsible for the minima of R Cr B variables (cf. Feast, 1979). Another case, similar to A30, has been recently reported by Peimbert (1981).

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DISCUSSION

KWOK: The mass loss formula used in stellar evolution calculations must reflect the mechanism(s) involved in that particular part of the HR diagram. There is good evidence that there are more than one mass loss mechanism at work for late-type stars. For example, coronae may cause mass loss in G, K stars, but unlikely to be responsible for M stars, which may rely on radiation pressure on dust, shock waves, or shock enhanced radiation pressure on dust. If one adopts a empirical approach, such as one mass loss rate (say 10^{-8} $M_{\odot}$ yr^{-1}) for G, K giants, another (say 10^{-6} $M_{\odot}$ yr^{-1}) for M stars, and 10^{-5} $M_{\odot}$ yr^{-1} for very late M stars, this, although primitive, may be more realistic than one generalized mass loss formula covering the whole H-R diagram, particularly in view of your calculation which finds the results extremely sensitive to the mass loss formula.

RENZINI: I think the current parametrization of the mass loss process, which considers a Reimers - like wind plus a "superwind" at the termination of the A GB phase, is the simplest and most effective option presently available.

ANDRIESSE: Can you say in short what happens with the mass distribution in a centrally condensed star when helium is ignited? In particular, does the energy liberated by these nuclear reactions lead to a decrease of the binding energy (potential energy)of the star? If so, do you admit that the fluctuation theory then predicts the superwind one needs to get planetary nebulae?

RENZINI: Following the core helium flash the stellar binding energy decreases by roughly a factor of 3. However, I believe that it is already established that the core helium flash does not trigger the complete envelope ejection, otherwise we would not have the observed HB stars. According to the current ideas, the core helium flash has nothing to do with the PN ejection, an event which occurs some 10^8 years later, when the star is at the termination of its AGB phase.

DUPREE: Ultraviolet spectra from IUE indicate a concentration of HB stars in the cores of globular clusters and a broader distribution of red giants. Dynamically, this suggests that the HB stars may be binaries. Would the evolution of binary systems reproduce the observed H-R diagram of globular clusters and, for istance, minimize the need for a "superwind" phase of single star evolution?

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RENZINI: Several thousand HB stars in globular clusters have been observed up until now, but none have shown signs of duplicity. Moreover, a search of main-sequence binaries in globular clusters has been completely unsuccessful until now (cf. Liller, Proc. I.A.U. Symp. N° 85, p. 357). On the other hand, I would say that in general it would be hard to understand the observed HB morphologies of globular clusters if a significant fraction of HB stars were binaries. However, I understand that most binaries could actually be confined in the dense central regions of a cluster, and binaries with proper initial separations would indeed produce hotter HB stars (cf. Renzini et al., 1977 , Astron. Astrophys. 56, 369). This could indeed have something to do with the UV excess observed in the core of a few clusters. Concerning the "superwind", it is actually required at the tip of the AGB and its connection with binarism is not straight forward at all.

GOLDBERG: Are the mass loss rates the only uncertain parameter entering into calculations of stellar evolution? For example, what effect do uncertainties in the opacities and other parameters have on the morphology of the HB and AGB?

RENZINI: Well, as everybody knows , the most uncertain ingredient in model calculations is the treatment of convection, but in our models convection has little to do with either the HB morphology or the extension of the AGB. These branches are only slightly affected, when allowance is made for the estimated uncertainties in opacity or nuclear-reaction rates. Similarly, more exotic phenomena, as meridional circulation and the like, have also little effect on the HB and the AGB. I think that there is general agreement among model makers that mass loss is really the key phenomenon determining the HB morphology and the AGB extension.