Part 1. Basic Facts, Structure, Evolution, Nucleosynthesis

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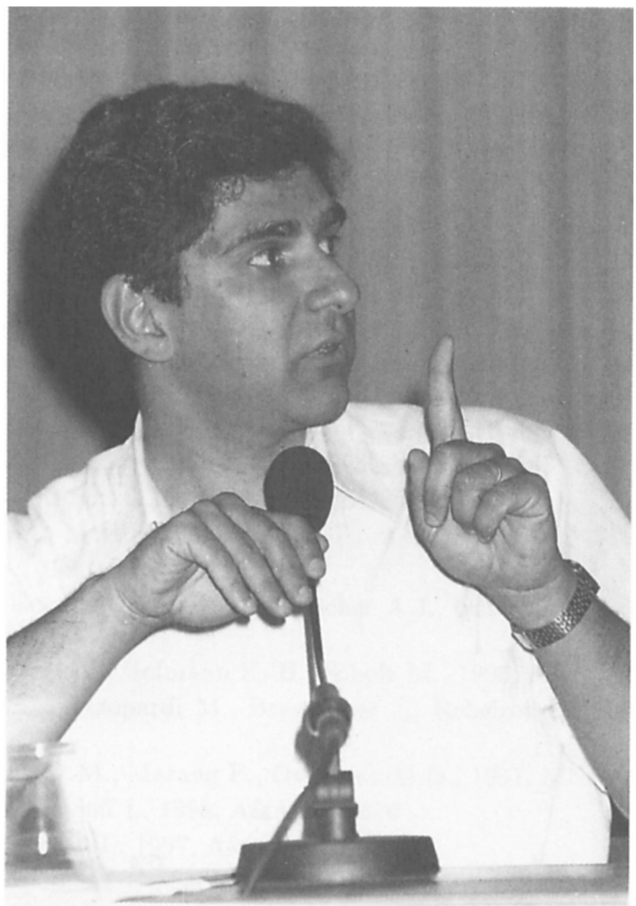

Basic facts, ... (Nami Mowlavi)

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Asymptotic Giant Branch Stars
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Structure and Evolution of AGB Stars

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Abstract. An overview of the structure and evolution of Asymptotic Giant Branch stars is presented. We focus upon the occurrence of thermal pulses, hot bottom burning and mass loss and summarize briefly the corresponding nucleosynthesis and mixing events. The interplay between these important evolutionary features is discussed.

1. Introduction

Single stars of *low* and *intermediate-mass* (~ 0.8 to $6 - 8M_{\odot}$) proceed after completion of central hydrogen and helium burning through the Asymptotic Giant Branch (AGB) phase before they finally end their evolution as white dwarfs consisting of carbon and oxygen (Weidemann & Koester 1983). The upper mass limit depends mainly on the size of the convective cores during the main sequence phase and thus is subject to the uncertainties of the convection prescription. Less massive stars ($\lesssim 0.8M_{\odot}$) cannot complete central hydrogen burning within a Hubble time whereas the more massive ones ($\gtrsim 6 - 8M_{\odot}$) are able to reach advanced burning stages, leading either (within a small mass range) to the formation of ONe white dwarfs after central carbon burning (Ritossa et al. 1996) or to the further evolution towards a supernova explosion.

After completion of central hydrogen burning on the main sequence, hydrogen burns in a shell around the He core. Due to core contraction the envelope expands. The star evolves towards larger radii and lower effective temperatures and ascends the Red Giant Branch (RGB). For low-mass stars, $M \lesssim 2M_{\odot}$, the He cores become electron-degenerate. Accordingly, they ignite central helium burning at the tip of the RGB under degenerate conditions (helium core flash) whereas intermediate-mass stars do it non-degenerately. During the evolution along the RGB the envelope convection moves downwards reaching layers which have previously experienced H-burning (*1st dredge-up*) leading to the mixing of processed material to the surface (Fig. 1).

After the subsequent central He burning the core consists of carbon and oxygen and is surrounded by two shells, one burning He and the other H. The star becomes a red giant a second time and ascends the Asymptotic Giant Branch. At first, He shell-burning dominates (Early AGB). For stars with $M \gtrsim 4M_{\odot}$ the outer convection can penetrate the hydrogen-exhausted layers leading to a considerable reduction of the core mass and to a second enrichment of the surface with CNO cycled material (*2nd dredge-up*). Later, hydrogen burning takes over and the helium-burning becomes recurrently unstable (Thermally Pulsing AGB). Fig. 1 illustrates the extent of the convective regions and burning

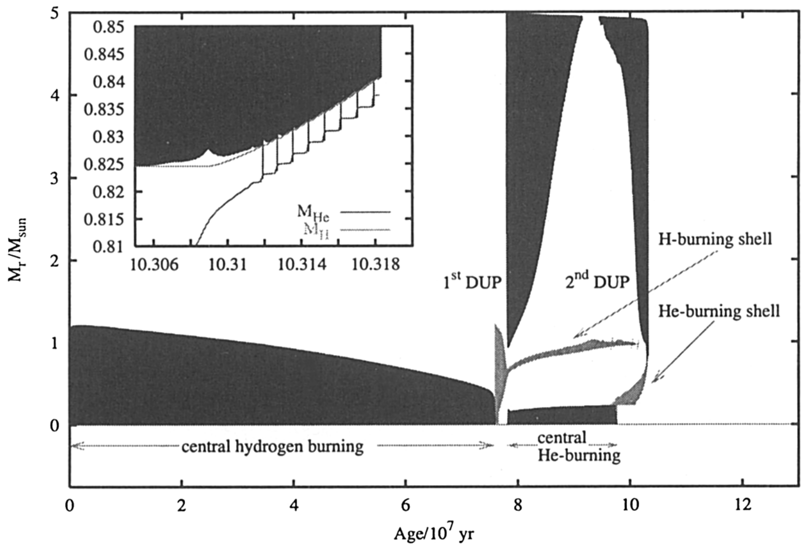

Figure 1. Mass-wise extension of convective regions and burning shells for a $5M_{\odot}$ model vs. time. Dark shaded regions refer to convectively unstable regions, light ones to the burning shells. The inlet shows the evolution on the upper AGB. The "spikes" correspond to the thermal pulses, $M_{\rm H}$ and $M_{\rm He}$ are the masses of the hydrogen and helium-exhausted core, respectively.

shells for different stages of evolution. The hydrogen-exhausted core of an AGB star is highly degenerate, it contains a substantial fraction of the stellar mass (~ 0.5 to $1M_{\odot}$) but the radial extent of its edge is only about 10^{-4} of that of the stellar surface. The C/O centre is surrounded by a thin layer of some $10^{-2}\,\mathrm{M}_{\odot}$ occupied by the He and H burning shells. Correspondingly, this core can be thought of as being a very hot white dwarf which grows in mass by accreting nuclear-processed matter from the envelope. Neutrino losses provide effective cooling of the core and postpone the ignition of carbon burning until the core has reached $1.4M_{\odot}$. However, mass loss prevents the cores from growing to such a critical size and terminates the AGB evolution well beforehand.

In the following sections we focus upon the evolution along the TP-AGB which is determined by the thermal instabilities of the helium burning shell (*thermal pulses*), the penetration of the convective envelope into the hydrogen burning shell for more massive objects (*hot bottom burning*), and strong and steeply increasing *mass losses.*

2. Mass loss

Stars evolving along the AGB suffer from continuously increasing mass loss. Observations indicate rates of $10^{-7}\,\mathrm{M}_{\odot}/\mathrm{yr}$ for small-period Mira stars and up to $10^{-4}\,\mathrm{M}_{\odot}/\mathrm{yr}$ for luminous long-period variables (Wood 1997). These winds

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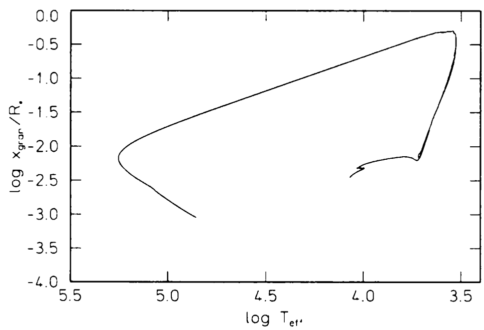

Figure 2. "Evolutionary track" for the diameter of surface granules given in stellar radii from the main sequence through the AGB towards the stage of white dwarfs for a $3M_\odot$ sequence with 20 pulses on the AGB

are most likely dust-driven supported by shock waves generated by the pulsating stellar envelope (Winters 1998) and lead at larger mass-loss rates to the complete obscuration of the star by a dusty circumstellar envelope. For reviews, see e.g. Habing (1996) and Winters (1998).

AGB stars exhibit a large-scale surface convection which may lead to inhomogeneities in the dust formation process and clumpy outflows (e.g. Weigelt et al. 1998). In contrast to their progenitors, the circumstellar shells of AGB successors often expose prominent features of asphericity. This change in the circumstellar shells geometry is supposed to take place either when the star moves off the AGB or already during its evolution along the upper AGB. It has been shown by Schwarzschild (1975) that for red giants the dominant convective elements may become so large that only a few of them can occupy the surface at any time leading to large temperature variations on the surface and concomitant brightness fluctuations. Hydrodynamical simulations for convection zones of main sequence stars and subgiants by Freytag et al. (1997) seem to support this scenario. They found a tight correlation between the photospheric pressure scale height, $H_{\rm p0}$, and the granule size, $x_{\rm gran}$, viz. $x_{\rm gran} \approx 10 H_{\rm p0}$ covering more than two orders of magnitudes in gravity. If one assumes that such a correlation also holds in the red giant regime, it indeed turns out that during the course of evolution, the granules become so large that the whole surface can be occupied by at most a few granules. Fig. 2 gives an "evolutionary track" for the granule sizes estimated from the correlation of Freytag et al. (1997) for a $3M_\odot$ sequence.

To consider mass loss in stellar evolution calculations one still has to rely on empirical relations or adaptions of (mass-loss) model grids. Recent approaches used in AGB model calculations are based on an empirical mass-loss – pulsation-period relation (Vassiliadis & Wood 1993), on a semi-empirical prescription derived from Bowen's (1988) hydrodynamical calculations of pulsating Mira atmospheres (Blöcker 1995a), and on a fit of wind models for carbon-rich stars (Arndt et al. 1997; Schröder et al. 1998). It is noteworthy that these prescriptions predict mass-loss rates that increase rapidly with luminosity and are considerably larger than those which would follow from the Reimers's formula (1975). Comparisons between the models of Vassiliadis & Wood (1993) and Blöcker (1995a) are given in Habing (1996), Wood (1997) and Blöcker (1998). Both sets are, within the observational errors, consistent with the empirical initial-final mass relation of Weidemann (1987). Note, however, that the uncertainties of such empirical relations are rather high, especially for large initial masses.

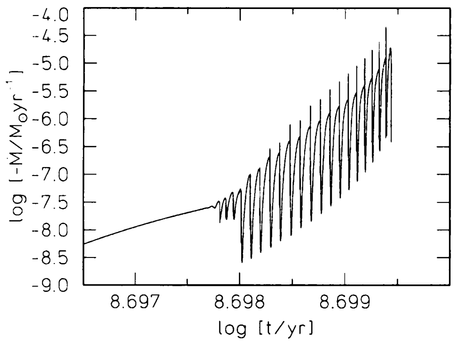

Figure 3. Evolution of the AGB mass-loss rate for a 3 $M_\odot$ model sequence (20 thermal pulses, Blöcker 1995a). The final mass is 0.625 $M_\odot$.

During the thermal pulses an AGB star does not only suffer from strong variations of its interior luminosity contributions but also from modulations of its surface luminosity and radius leading to corresponding mass-loss variations. Fig. 3 shows as an example the whole mass-loss evolution along the AGB for a 3 $M_\odot$ model sequence. One clearly sees how thermal pulses lead to order-of-magnitude modulations or short interruptions of the otherwise monotonically increasing mass-loss rate. The corresponding path in the two colour diagram is triggered by these flash-induced mass-loss modulations leading to recurrent loops. Detached dust shells can develop and during the pulses the stars can spend about 10 % of their life away from the main IRAS two-colour relation of dusty AGB stars (Steffen et al. 1998). Thus, mass-loss modulations by thermal pulses seem to account for the observed detached shells and loops in the IRAS two-colour diagram (van der Veen & Habing 1988; Olofsson et al. 1990; Zijlstra et al. 1992; Izumiura et al. 1996).

Finally, mass loss terminates the AGB evolution when the envelope mass is reduced to a few $\approx 10^{-2}\,M_\odot$. The star moves off the AGB (Schönberner 1979) evolving towards the regime of central stars of planetary nebulae and finally reaches the stage of white dwarfs. Even beyond the AGB the evolution depends on the preceding mass-loss history. Since mass loss determines the life-time on the AGB, it determines not only the final mass but also the internal temperature-density structure reached at the tip of the AGB and, thus, the timescales for the evolution into a white dwarf (Blöcker 1995a, b).

3. Hot bottom burning

As the stars evolve towards larger luminosities along the AGB, their envelope convection extends further downwards. For $M > 4...5\,M_\odot$ (depending on metallicity) the bottom of the convective envelope can even reach and dip into the H-burning shell (hot bottom burning, HBB; Iben 1975; Scalo et al. 1975). The consequences for stellar evolution are far reaching: the bottom of the envelope burns with temperatures of typically 30 to $80 \cdot 10^6$ K and the processed material is immediately convected to the surface. HBB models evolve rapidly to very high luminosities and no longer obey Paczyński's (1970) classical core-mass luminosity relation (Blöcker & Schönberner 1991).

The CNO-cycling of the envelope in HBB models destroys ^{12}C and builds up ^{14}N and ^{13}C. Accordingly, the typical signature for HBB is a low $^{12}C/^{13}C$

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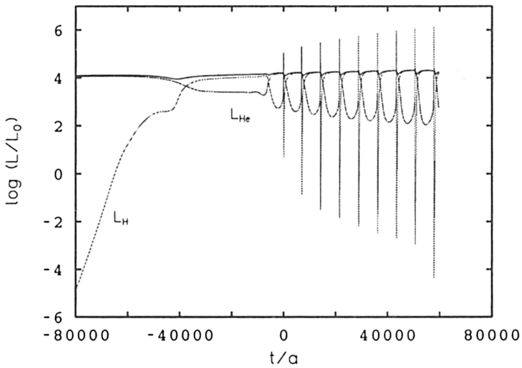

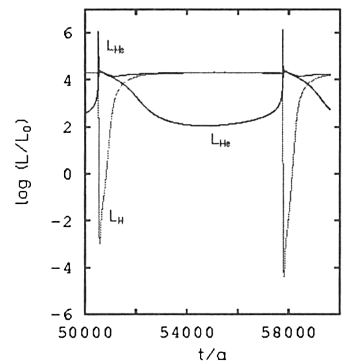

Figure 4. **Left:** Surface luminosity and shell-source contributions on the AGB for a $5M_\odot$ model (Blöcker 1995a). **Right:** The last two pulses on an expanded scale.

ratio and the delay or even prevention of the carbon-star phase (e.g. Iben 1975; Renzini & Voli 1981; Boothroyd et al. 1993). HBB leads to the formation of lithium-rich stars (Scalo et al. 1975) via the Cameron & Fowler (1971) mechanism which first synthesizes ^{7}Be and then convects it to cooler regions where ^{7}Li is finally formed. Observations in the Magellanic Clouds show that Li-rich stars are only found between $M_{\rm bol} \approx$ -6 to -7 (Smith & Lambert 1989, 1990; Plez et al. 1993) and the results from evolutionary calculations (Sackmann & Boothroyd 1992; Forestini & Charbonnel 1997) are in very good agreement with these findings. However, Li-rich galactic carbon stars are observed at much lower luminosities, $M_{\rm bol} \approx$ -3.5 to -6, indicating that possibly additional mixing processes operate in these stars (Abia & Isern 1997) such as, e.g., the so-called cool bottom processing by deep circulation (Wasserburg et al. 1995).

4. Thermal pulses

Early numerical calculations of AGB models showed that burning hydrogen and helium simultaneously in two shells is thermally unstable in the sense that the helium-burning shell repeatedly enters into run-away situations (Schwarzschild & Härm 1965; Weigert 1966). For more details, see e.g. Iben & Renzini (1983). Fig. 4 illustrates the typical luminosity evolution of both shells for a $5M_\odot$ model after completion of central He burning until the onset of the first pulses. With the onset of a thermal pulse the luminosity of the He-burning shell increases rapidly within a short time of about 100 yrs to $10^6 ... 10^7$ L$_\odot$. During this phase the He shell is forced to become convectively unstable due to the huge amount of energy produced: a pulse-driven convective zone develops which comprises almost the whole intershell region and mixes products of He burning, in particular C (and O), outwards (see Figs. 1 and 5). Simultaneously, the H-shell is pushed outwards into cooler domains and extinguishes. After the flash, the envelope convection proceed downwards, may penetrate deeply into those intershell layers formerly enriched by the flash-driven intershell convection, and mixes this material to the surface. This is the *3rd dredge-up* which may change the envelope C/O ratio

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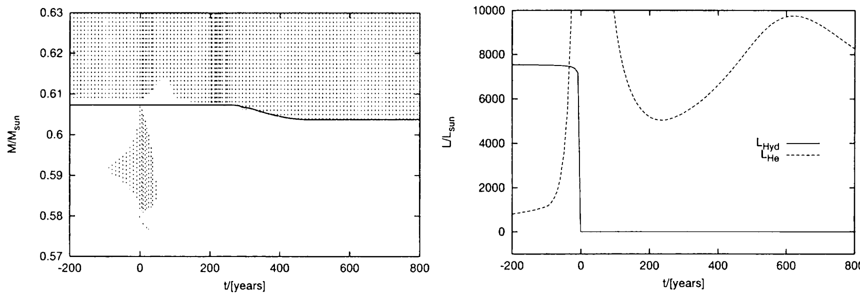

Figure 5. Extension in mass of convective regions (left) and luminosity contributions of the shell sources (right) vs. time for the 12$^{\mathrm{th}}$ pulse of a $3\mathrm{M}_\odot$ AGB star (Herwig et al. 1997). Time is set to zero at maximum L_{He} ($\sim 10^6\,\mathrm{L}_\odot$). The solid line denotes the border of the hydrogen exhausted core. Shaded regions indicate convective mixing. He burning takes place between $M_{\mathrm{r}} = 0.585$ and $0.570\,\mathrm{M}_\odot$.

from smaller than unity to larger than unity, i.e. lead to the formation of carbon stars. Fig. 5 shows the dredge-up episode of a $3\,\mathrm{M}_\odot$ AGB model. In this example the flash-driven convective zone exists for 150 yr. Dredge-up starts 250 yr after this convective shell has disappeared. Hydrogen re-ignites 5 000 yr later, and the next pulse commences after further 60 000 yr of evolution. Recently, Frost et al. (1998a) reported that very deep dredge-up may lead to the ignition of He under partially degenerate conditions.

H burning remains virtually extinguished during the first $\sim 15\%$ of the cycle time, and He burning provides the surface luminosity. Then, H burning is restored and controls the evolution. Typically, a thermal-pulse cycle lasts several 10^3 up to 10^5 yrs depending on core mass. The large energy excess liberated during a pulse is temporarily stored as potential energy and re-radiated later on a much longer time scale. Therefore, the changes at the stellar surface, i.e. of its radius and luminosity, are much smaller than the many order-of-magnitude variations of the shell luminosities themselves but may lead to considerable modulations of other quantities such as, e.g., mass-loss rates (Fig. 3).

The intershell region of AGB stars is also the site of s-process nucleosynthesis (e.g. Gallino et al. 1998). Two possible reactions provide the necessary neutrons: $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ and $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$. The temperatures reached in the intershell zone during thermal pulses appear to be too low to activate the $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ reaction. Instead, the s-process is most likely driven by the $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ neutron source. This requires the mixing of protons into $^{12}\mathrm{C}$-rich layers in order to produce sufficient amounts of $^{13}\mathrm{C}$ via $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}(\beta^+,\nu)^{13}\mathrm{C}$. Iben & Renzini (1982) found that the protons can diffuse from the bottom of the convective envelope into the intershell zone due to semiconvection. However, this scenario is restricted to low metallicities (Iben 1983). To follow the s-process under typical conditions one has to artificially ingest a certain amount of $^{13}\mathrm{C}$ at the proper time (e.g. Straniero et al. 1995).

The question of burning and mixing along the AGB is intimately linked to the so-called *carbon star mystery* (Iben 1981): observations of the LMC and

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SMC prove that most of the carbon (and s-process element) enriched AGB stars are found at rather low luminosities ($M_{\rm bol} > -6$) indicating that they are *lower mass* stars (cf. Smith et al. 1987, Frogel et al. 1990). On the other hand, AGB models mostly predict the $3^{\rm rd}$ dredge-up for much higher luminosities, i.e. larger (core) masses.

The lack of luminous carbon stars is likely to be explained in terms of hot bottom burning and mass loss. HBB can turn the carbon enriched envelopes of massive (and therefore luminous) models into nitrogen-rich ones. Furthermore, HBB models do not obey Paczyński's (1970) classical core-mass luminosity relation but evolve rapidly towards large luminosities. On the other hand, the steeply increasing AGB mass-loss rates do not allow a very long evolution on the upper AGB and may terminate the evolution before the carbon-star stage is reached (Iben 1981; D'Antona & Mazzitelli 1996). Finally, the continuous erosion of the stellar surface by stellar winds leads to obscuration by dust which may hide luminous carbon stars from optical surveys (Iben 1981). Indeed, van Loon et al. (1998) observed obscured carbon stars in the Magellanic Clouds which are brighter than $M_{\rm bol} = -6$. Whether luminous carbon stars can be formed depends crucially on the competition between dredge-up and HBB which both require minimum envelope masses to operate and thus depend on the assumed mass-loss evolution (and treatment of convection). Frost et al. (1998b) found that HBB ceases earlier than dredge-up during the superwind phase when the star is expected to be dust-enshrouded. Dredge-up continues and leads to the formation of a carbon star.

The second problem concerns the difficulties in obtaining dredge-up for models of the observed mass range. The amount of dredge-up found in evolutionary calculations depends sensitively on metallicity, core and envelope masses (Wood 1981), and is in any case too small to account for the observations. Additionally, numerical details may play an important role (Frost & Lattanzio 1996). The cause of the large uncertainties concerning the efficiency of dredge-up is in particular our inability to treat convection properly. Accordingly, this affects the question of how to form ^{13}C as well.

Synthetic AGB calculations, therefore, utilize stellar parameters known from evolutionary AGB model sequences but take the minimum core mass for dredge-up, $M_{\rm H}^{\rm min}$, and the dredge-up parameter λ (ratio of dredged-up mass to growth of $M_{\rm H}$ per flash cycle), as adjustable parameters (among others) in order to match the observations, i.e. the luminosity function of LMC carbon stars. For example, Marigo et al. (1996) and van den Hoek & Groenewegen (1997) find $M_{\rm H}^{\rm min} = 0.58\,{\rm M}_\odot$ and $\lambda = 0.65$ and 0.75, resp., as best fit contrasting the results of evolutionary calculations ($M_{\rm H}^{\rm min} \gtrsim 0.65\,{\rm M}_\odot$ and $\lambda \approx 0.25$, see Wood 1997).

Due to these uncertainties of stellar evolution calculations and their weakness to face the observations, it is often concluded that mixing may take place outside the formally convective boundaries (Iben 1976; D'Antona & Mazzitelli 1996; Wood 1997). Recently, Herwig et al. (1997) introduced overshoot based on the results of hydrodynamical simulations of convection by Freytag et al. (1996) in their treatment of convection. The parametrisation of exponentially decreasing velocities of convective elements beyond the classical convective border then leads to some extra partial mixing (Blöcker et al. 1998). This method provided for AGB stars with rather *small* core masses of $\sim 0.6\,{\rm M}_\odot$ *both* a sufficient amount of dredge-up (note, however, that Straniero et al. (1997) found dredge-up for low core masses without additional mixing) *as well as* the production of ^{13}C. It should be noted that a ^{13}C pocket formed during the dregde-up phase will not survive until the onset of the next pulse. Due to the high temperatures reached in the intershell region in the course of evolution it is already burnt during the interpulse phase and will not be engulfed by the next flash-driven convection zone (Straniero et al. 1995). Accordingly, the s-process takes place in a radiative environment (Gallino et al. 1998).

Further consequences of this additional mixing are the drastically changed intershell abundances of (^{4}He,^{12}C,^{16}O) = (40/40/16) by mass (see Herwig et al. 1998b) compared to standard calculations which give (70/26/1). It is noteworthy that these modified intershell abundances are close to the observed surface abundances of Wolf-Rayet central stars of planetary nebulae and PG 1159 stars. The evolutionary history of these H-deficient post-AGB stars is not well understood. One scenario discussed is that of a final thermal pulse after the cessation of H-burning on the white dwarf cooling track which predicts surface abundances close to those of the intershell region (Iben & MacDonald 1995). On the other hand, there is evidence that the observed abundance pattern has already developed immediately after the star has moved off the AGB (Werner et al. 1998). In any case, it appears promising that overshoot models may provide a better understanding of these objects.

Regardless of the mixing approach invoked to be in accordance with the observations, the occurrence of effective dredge-up has another important consequence. As reported by Herwig et al. (1998a) models with efficient dredge-up ($\lambda \to 1$) and lower core masses ($\lesssim 0.8 M_\odot$, i.e. lower than those associated with hot bottom burning) violate Paczyński's (1970) classical core-mass luminosity relation. Even when the core-mass growth is completely compensated by dredge-up the luminosity still increases. Homology relations show that, in principle, the luminosity depends on *both* core mass *and* core radius. For core masses $\lesssim 0.8 M_\odot$ one typically obtains $L \sim M_{\rm H}^2/R_{\rm H}$. For instance, models without dredge-up show (after some pulses) an almost linear core-radius decrease with increasing core mass leading to the classical linear core-mass luminosity relation. On the other hand, strong dredge-up of $\lambda = 1$ cancels the core-mass dependence while the core radius continues to decrease. Accordingly, the luminosities evolve to higher values than predicted by Paczyński's (1970) relation.

5. Conclusions

Along the AGB mixing episodes are able to dredge up products of the interior nucleosynthesis to the surface whereas simultaneously strong stellar winds erode effectively the stellar envelopes leading to an enrichment of the interstellar medium with processed material. The envelope's chemical evolution and thus the composition of the stellar ejecta depends crucially on the treatment of convection and mass loss. The course of mass-loss evolution is not well known, and due to the drawbacks of the local treatment of convection additional mixing processes seem to be required during various phases of evolution. The important interplay between mass loss, mixing and nucleosynthesis and its implications for the structure and evolution of AGB stars remains to be investigated in more detail.

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