STELLAR EVOLUTION AND NUCLEOSYNTHESIS OF POST-AGB STARS

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Abstract I discuss recent new models of post-Asymptotic Giant Branch stellar evolution. These models aim to clarify the evolutionary origin and status of a variety of hydrogen-deficient post-AGB stars such as central stars of planetary nebulae of Wolf-Rayet spectral type, PG1159 stars or Sakurai's object. Starting with AGB models with overshoot stars can evolve through one of four distinct channels. Each of these channels has typical abundance patterns depending on the timing of the departure off the AGB and the occurrence of the last thermal pulse. I discuss the responsible mechanisms and the respective observational counterparts.

1. INTRODUCTION

Nuclear burning and mixing processes in post-Asymptotic Giant Branch (pAGB) stars are closely related to the last thermal pulse (Iben, 1995). If the last thermal pulse (TP) occurs well before the departure from the AGB the pAGB stage will proceed undisturbed. However, if the last TP occurs immediately before the departure off the AGB (AFTP case) or during the early (LTP case) or the late post-AGB phase (VLTP case), then internal mixing and possibly as well nuclear burning processes will lead to distinctive alterations of the surface abundances. For example, the hydrogen-deficiency of central stars of planetary nebulae of Wolf-Rayet spectral type ([WC]-CSPN) is the result of such an abundance alteration as concluded from their large helium, carbon and oxygen abundance and the lack of hydrogen in their spectra (Koesterke and Hamann, 1997).

The last TP effects other elements as well. This is supported by the weird abundance pattern of Sakurai's object which is apparently a Born-again AGB object (Asplund et al., 1999). It shows a real-time evolution of lithium, hydrogen, s-process elements and others. Hybrid objects - with an intermediate hydrogen abundance between [WC]-CSPN and H-normal stars - are as well associated with a non-standard pAGB evolution (Napiwotzki et al., 1991). Post-

AGB evolutionary scenarios which involve a thermal pulse are in a couple of ways closely related to the proto-planetary phase of pAGB evolution.

As described by Herwig (2000b) and Blöcker (2000) the occurrence of the last TP determines the further evolution along the pAGB and finally the WD stage. The thermal pulse is a thermonuclear instability of the He-shell and accordingly no TP can occur after He-burning ends at the latest at the pre-WD stage of pAGB evolution. On the AGB TPs are recurring mainly independently of mass loss on a timescale of a 10^4 to $10^5\,\mathrm{yr}$.

The AGB evolution is ended randomly by mass loss which strips the envelope off the core. If the envelope mass decreases below a critical value of about $0.001\,\mathrm{M}_\odot$ contraction sets in and the star will begin its evolution along the horizontal part of pAGB evolution in the HRD. The last TP which occurs in the lifetime of a star may be past a few thousand years when the AGB star starts contraction to evolve into a central star. In that case this last TP does not interfere with an undisturbed and hydrogen-rich pAGB evolution finally leading to a white dwarf of spectral type DA.

However, if by coincidence the last thermal pulse occurs either immediately before or within a certain time interval after the transition towards the central star phase then a severely different evolution must be expected. In the following sections I will discuss in turn the three channels of evolution in which the last thermal pulse interferes with an undisturbed pAGB evolution.

2. THE AGB FINAL THERMAL PULSE

We found in our calculations of AGB models with overshoot that dredge-up is much more efficient if overshoot is not only applied to the bottom of the envelope convection zone but as well to the He-flash convection zone in the intershell during the thermal pulse (Herwig et al., 1997; Herwig, 2000a). While the third dredge-up is usually difficult to find in stellar models of low core mass and low envelope mass we did find dredge-up after the last TP still on the AGB at a surprisingly low envelope mass of $4 \cdot 10^{-3}\,\mathrm{M}_\odot$. This dredge-up was found under the assumption of an increased efficiency of convective mixing ($\alpha_{\mathrm{MLT}} = 3.0$) and overshoot with an efficiency parameter of $f = 0.016$. The amount of dredged-up material was of the order of $6 \cdot 10^{-3}\,\mathrm{M}_\odot$ `check this!!`.

In the AFTP case the last thermal pulse coincidently occurs when the envelope mass is already very close to the critical envelope mass which marks the departure off the star from the AGB regime. The remaining envelope mass and the amount of dredged-up mass are of comparable quantity and therefore the surface abundance change due to dredge-up is considerable. If the star is oxygen-rich before this final thermal pulse it will turn into a carbon star during this final dredge-up episode, just at the onset of the proto-planetary transition phase. This carbon star is different from the carbon stars known on the AGB in that its carbon abundance is much larger. In fact, after an AFTP dredge-up episode as described above the emerging central star is hydrogen-deficient. The extent of H-deficiency depends on the amount of envelope mass at the last thermal pulse and the efficiency of dredge-up after this last TP. As an example, the two AFTP calculations by Herwig (2000b) produced central stars with mass fractions of (H/He/C/O) of (0.55,0.31,0.07,0.04) and (0.17,0.33,0.32,0.15).

This evolutionary scenario has considerable observational support. Planetary nebulae (PNe) of [WC]-type hydrogen-deficient central stars are on average not older than PNe surrounding chemically normal central stars (Zitat). This has been taken as an indication that these H-deficient central stars are on their first evolutionary departure off the AGB. The alternative evolutionary scenario described below, in particular the very late thermal pulse, would rather require H-deficient central stars to have old PNe since they are supposed to be on their second departure off the AGB following a Born-again evolution which might last more than $10^4\,\mathrm{yr}$. Thus, the AFTP scenario would naturally resolve the time scale problem of PNe around H-deficient CSPN.

Recent ISO observations support the AFTP scenario as well as reported by Waters et al. (1998). They found both oxygen and carbon rich dust around hydrogen-poor pAGB stars. This discovery is rather surprising since carbon rich dust (PAH=Polycyclic Aromatic Hydrocarbon) and oxygen rich dust (crystalline silicates) usually exclude each other. If the number ratio C/O exceeds unity in the dust forming gas all oxygen is locked up in CO molecules and only C-rich dust can form. The opposite is true if C/O<1. Consequently the simultaneous presence of oxygen and carbon rich dust must be the result of a recent change of surface abundance pattern in the mass loosing star. The AFTP scenario does actually provide such a sudden abundance change immediately before the onset of the pAGB phase. In this picture the oxygen rich AGB star evolves towards the last thermal pulse with presumably high mass loss and experiences efficient dredge-up of intershell material which has a C/O ratio of about $3 \dots 4$. Instantly the star will become carbon rich. Possibly the now carbon rich surface composition will once more enhance mass loss and accelerate the evolution towards the pAGB phase. The timescale of the abundance change and the following transition evolution off the AGB are around $1000\,\mathrm{yr}$, in agreement with the timescales inferred for the abundance change from the ISO observations of the circumstellar dustshell.

If *all* [WC]-late CSPN show the signature of simultaneous presence of oxygen and carbon rich dust (for a discussion of this possibility see the contribution by Hony et al., these proceedings) some interesting conclusions can be drawn. The first is that *all* [WC]-late type CSPN are originating from an AFTP because this is currently the only scenario we know which provides the sudden and drastic abundance change being past less or about $1000\,\mathrm{yr}$ as implied by the ISO observations. This raises the question why there are no [WC]-late type descendants of the LTP or VLTP evolution (see below) in their second departure off the AGB. This would in particular imply that a star like Sakurai's object would not show up as a [WC]-late type CSPN. This conclusion might actually be supported by `Abell 78 ... check this out`. The second consequence would be that an AFTP predominantly occurs in oxygen rich AGB stars (S- and M-giants) because an AFTP event occurring in a C-star could not be hosting a circumstellar dust shell which contains crystalline silicates.

One way to understand the latter conclusion is a different dependence of mass loss on the stellar parameter variation during a thermal pulse for oxygen rich stars as opposed to carbon rich stars. The probability for the occurrence of an AFTP is greatly enhanced if the mass loss rises steeply at the onset of the thermal pulse. While under the assumption of constant mass loss throughout the thermal pulse cycle the fraction of AGB stars entering into an AFTP evolution is small ($\sim 1 \ldots 3\%$) this fraction can be very much enhanced if a strong mass loss is correlated with the thermal pulse because this strong mass loss during the thermal pulse correlates the occurrence of the TP with the immediately following departure off the AGB caused by the diminished envelope mass. If the assumptions that *all* [WC]-late central stars show the signature of simultaneous presence of oxygen and carbon rich dust is confirmed then one implication within the AFTP scenario would be that M- and S-stars have considerably larger mass loss associated with the actual thermal pulse than C-stars. The latter are then apparently not able to trigger immediate departure off the AGB after a final thermal pulse by large TP mass loss. Instead they possibly have their mass loss more evenly distributed over the TP cycle and thus an AFTP sequence of events is less likely than for oxygen-rich AGB stars.

3. THE LATE THERMAL PULSE

While in the AFTP case the last TP on the AGB is immediately followed by the transition of the star towards the pAGB phase the order of events is reversed in the LTP case. The departure off the AGB begins up to about $5000\,\mathrm{yr}$ before the last TP. Accordingly the star will be disturbed by a TP during the pAGB evolution which leads to a Born-again evolution back to the AGB. This evolutionary scenario is closely related to the VLTP described below with one main distinction. In the LTP case the H-shell has not yet ceased at the time of the TP. As a consequence the star will not experience the violent nuclear processes induced by the ingestion of the H-rich envelope material into the He-flash convection zone as found for VLTP models (see below). Instead, Blöcker (2000) and Herwig (2000b) found that another dredge-up during the Born-again AGB stage after the LTP may lead to abundance alterations which would be in accordance with abundances of [WC]-CSPN as well (see as well `IBEN: convective drift`). If the time interval between the departure off the AGB and the TP is small this scenario could even account for the normal ages of PNe around [WC]-CSPN. Moreover this evolutionary channel more naturally leads to the very low H-abundances actually observed in the late-type [WC]-CSPN. The envelope mass is by definition of the order of $10^{-4}\,\mathrm{M}_\odot$ when the star has entered the CSPN stage and the TP occurs. In the LTP calculation by Herwig (2000b) the amount of dredged-up material is of the order of a few $10^{-3}\,\mathrm{M}_\odot$ and the resulting surface mass fractions are (H/He/C/O)=(0.02,0.37,0.40,0.18).

Taking into account the comparatively large mass loss of [WC]-CSPN of $\dot{M} \sim 10^{-6}\,\mathrm{M}_\odot$ (Koesterke and Hamann, 1997), it is conceivable that a pAGB star after a LTP Born-again event loses it's entire top layer during the second evolution off the AGB. This top layer represents the region well mixed during the dredge-up after the LTP and consists of the just mentioned amount of a few $10^{-3}\,\mathrm{M}_\odot$. If this striping of the outer dredge-up layer is possible for a LTP descendent star then the LTP evolution could even yield non-DA WDs which do not contain any hydrogen at all.

One of the unsolved problems with this scenario is the description of mass loss during the second, Born-again AGB phase when the abundance suddenly and dramatically changes due to the dredge-up. The large amounts of carbon and oxygen brought to the surface could initiate a rapid increase in dust formation and thereby mass loss.

4. THE VERY LATE THERMAL PULSE

The VLTP is similar to the LTP in that the last TP occurs after the departure off the AGB. However, the time interval between the AGB departure and the TP is longer, typically exceeding $\sim 5000\,\mathrm{yr}$. At this time hydrogen burning in the shell has already stopped and the entire envelope material will be included in the convective He-burning region (see Herwig et al. (1999) and Herwig (2000b) for details and references). The star takes a deep loop through the HRD in order to return to the AGB again, similar to the LTP case. While the VLTP model abundances agree with the observations of [WC]-CSPN, the PNe timescale problem is most severe for this case. Before the potential of the LTP and the AFTP to provide scenarios for the origin of the H-deficient [WC]-CSPN and PG1159 was realized the VLTP was thought to be the only possible evolutionary origin of these objects (Iben and MacDonald, 1995). Now, its significance arises mainly due to the unique mode of convective nucleosynthesis originating from the ingestion of protons from the unprocessed envelope into the He-flash convection zone. The nuclear burning and mixing both occurs on the time scale of about one hour once the protons have reached sufficient temperature while being transported inward by convection. Temporarily and locally the luminosity of hydrogen burning exceeds the peak-flash He-burning luminosity. The He-flash convection zone is fragmented. In these exceptional conditions we have

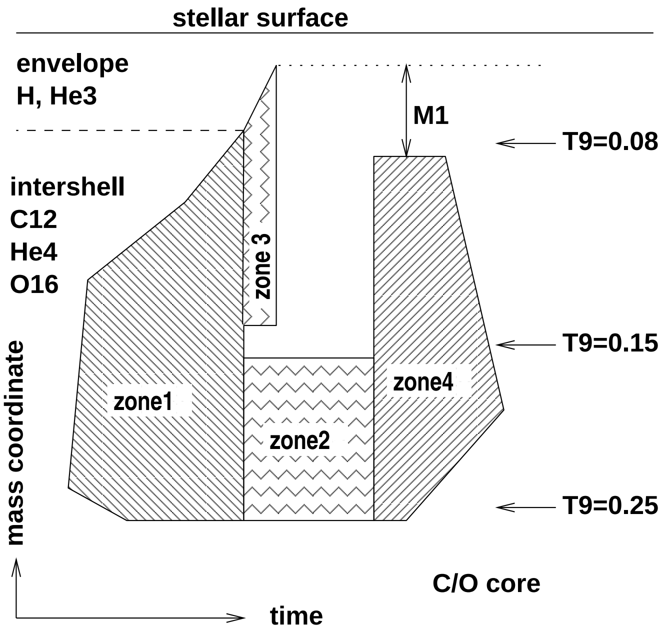

Figure 1 Schematic (not to scale) of the time-evolution of convection zones in the top $0.01\,\mathrm{M}_\odot$ of a post-AGB star of $0.6\,\mathrm{M}_\odot$ during a VLTP. All shaded areas indicate convectively unstable zones. Tempertures are indicated in units of 10^9 K on the right side. Solid horizontal line at the top of the diagram: the stellar surface, dashed line: mass coordinate of the envelope-intershell transition.

identified a new mode of light-element nucleosynthesis (Herwig Aarhus) which could be of importance in order to explain the unusual abundance pattern of Sakurai's object, in particular it's high lithium abundance (Herwig Keele).

The nucleosynthesis during the VLTP is highly dependent on the details of convective mixing because here both processes are closely related. While the protons from the envelope enter an hotter environment on their way down into the He-flash convection zone their nuclear burning time scale diminishes. At the position where it matches the convective turnover time scale the greatest part of the hydrogen-burning luminosity will be created. Therefore the position in the star where the peak H-burning luminosity can be found will depend both on the assumptions of efficiency of convective mixing as well as the numerical treatment of the simultaneous burning and mixing.

For the calculation by Herwig et al. (1999) we developed a fully coupled numerical scheme for convective nucleosynthesis. The equations of material transport (one diffusion-like equation for each isotope) and the nuclear network equations at each depth mass grid are solved altogether fully implicit in one scheme. This treatment returns consistent abundance profiles within the con-

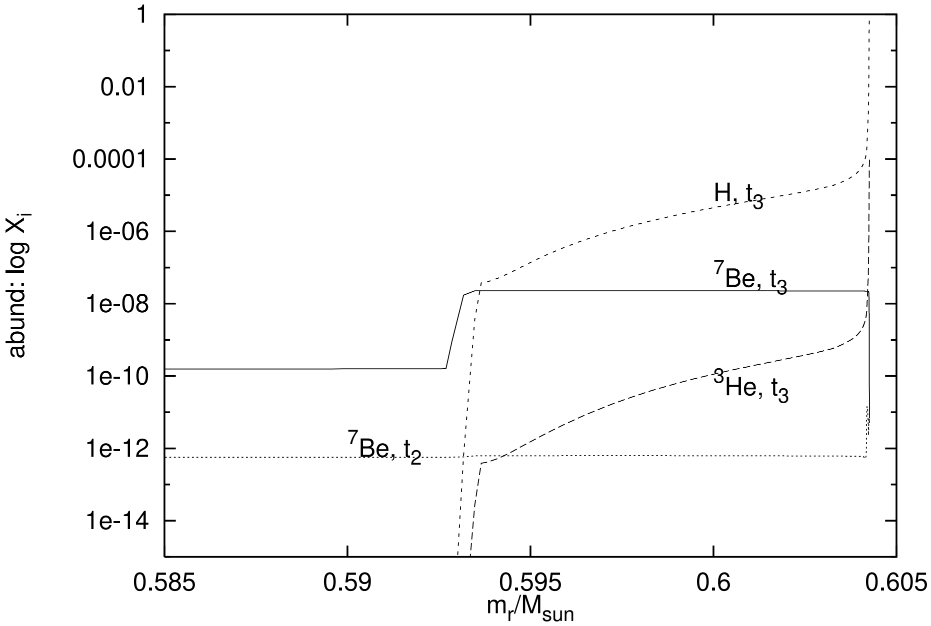

Figure 2 Abundance profiles during the VLTP including light elements.

vective region. Thus, the energy generation rates calculated as a function of position in the stellar burning region reflects the rapid consumption of protons in the He-flash convection zone at each position consistently.

The evolution of the pulse-driven convection zone during a VLTP model sequence is sketched in Fig. 1. It shows the sequence of events found in the models of Herwig et al. (1999). The convective instability can be divided in four different regions. Zone 1 represents the onset of the He-flash. During this first phase the He-burning luminosity increases by several orders of magnitude. It is essential the same evolution as during the onset of any AGB thermal pulse or the LTP. The difference occurs when the upper boundary of the He-flash convection zone approaches the H-rich envelope (second horizontal line from top in Fig. 1). In the VLTP case the convective instability reaches out of the intershell and spreads into the H-rich envelope as represented by zone 3 in Fig. 1. This is not possible in the LTP case or during typical AGB thermal pulses because there the H-burning shell is still active at the time of the thermal pulse (Iben, 1976). The fresh nuclear fuel which is ingested into the deeper and hotter region burns on ever shorter timescales while at the bottom of zone 2 the unstable He-burning continues mainly undisturbed.

Due to the locally large energy generation of up to $10^8\,\mathrm{L}_\odot$ by H-burning a small radiative layer between zone 2 and 3 establishes. This radiative layer effects the permeability for particle transport from zone 2 to 3. If the efficiency of overshoot is large a considerable fraction of freshly produced particles, e.g. $^{13}\mathrm{C}$ will be burned at the bottom of zone 3 instead of the bottom of zone 2. Thus, the assumed overshoot efficiency has an important influence on the model predictions. Moreover the position of the split between zone 2 and 3 depends on the assumption of convective efficiency. For a larger convective efficiency the mass coordinate of peak H-burning luminosity and thereby of the split shifts inwards and accordingly the maximum temperature ruling the nucleosynthesis in zone 2 increases.

The additional energy supply by proton captures causes zone 2 to stretch out and engulf the entire envelope. The moment of abundance change at the surface due to the mixing of zone 2 depends on the initial conditions of the VLTP. On one extreme is the immediate abundance change after the VLTP while the star still resides in the blue and faint part of the Born-again loop in the HRD. This will only occur for the most vigorous cases of proton burning during the VLTP. In other cases a tiny layer of original envelope material of less than $10^{-6}\,\mathrm{M}_\odot$ may cover the changed abundances close to the surface until during the evolution back to the AGB either mass loss or the onset of convection will reveal the H-poor abundance.

In any case, zone 3 is only shortlived due to the restricted amount of hydrogen available in the envelope. If that amount is consumed the related convective region will die away. After some cooling of that layer the original He-flash convection zone resumes control (zone 4). Note, that the most outward reach of zone 4 is smaller than that of zone 3. In the layer swept over by zone 3 but not by zone 4 an element distribution formed in zone 3 only can be preserved close enough to the stellar surface in order to show up later on. It is here were we suspect lithium to form according to the mechanism of *hot hydrogen-deficient* $^{3}\mathrm{He}$ *burning* as described in Herwig & Langer (Herwig and Langer, 2000). This lithium would be in agreement with the lithium abundance observed in Sakurai's object (Asplund et al., 1999) which is believed to be a VLTP star caught in its Born-again evolution.

The VLTP does provide as well a rich neutron capture nucleosynthesis initiated by the production of $^{13}\mathrm{C}$ in zone 3 (Fig. 1). The neutrons are partly released immediately by the well known $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ reaction. Alternatively $^{13}\mathrm{C}$ is stored in the region covered by zone 3 until the He-flash convection zone recovers from the disturbation of H-burning. Then $^{13}\mathrm{C}$ burns at a higher temperatures in zone 4. Future models of the s-process during the VLTP should predict a distinctive heavy-element signature to be compared with that of Sakurai's object.

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