Modeling the evolution of Sakurai's object

Falk Herwig
Institut für Physik, Astrophysik, Universität Potsdam, Potsdam, Germany
Institute for Physics and Astronomy, University of Victoria, Victoria BC, Canada
(fherwig@uvastro.phys.uvic.ca)

December 8, 2000

Abstract. Sakurai's object is a born again AGB star of the *very late thermal pulse* flavor. In this contribution I will discuss new models of stellar evolution and nucleosynthesis models of this phase. Two most intriguing properties of Sakurai's objects have so far not been understood theoretically: the peculiar chemical appearance, in particular the high lithium abundance and the short time scale of only a few years on which the transition from the dwarf configuration into the born again giant appearance has occurred. A new nucleosynthesis mode of *hot hydrogen-deficient* ^{3}He *burning* can explain the extraordinary lithium abundance. During the thermal pulse ^{3}He is ingested from the envelope together with the protons into the hot He-flash convection zone. The first network calculations show that due to the large ^{12}C abundance protons are rather captured by carbon than destroy newly formed ^{7}Be and ultimately ^{7}Li. Moreover, the short evolution time scale has been reproduced by making the assumption that the convective efficiency for element mixing is smaller by two to three orders of magnitude than predicted by the mixing-length theory. As a result the main energy generation from fast convective proton capture will occur at a larger mass coordinate, closer to the surface and the expansion to the giant state is accelerated to a few years in excellent agreement with Sakurai's behavior. This result represents an independent empirical constraint on the poorly known efficiency of element mixing in convective zones of the stellar interior.

Keywords: Stars: AGB and post-AGB, abundances, evolution, interior, individual: V4334 Sgr

1. Introduction

Sakurai's object (V4334 Sgr) has remarkable properties which likely make it one of the most interesting stellar objects currently investigated. Surrounded by a planetary nebula it has evolved dramatically in recent years both in stellar parameters and in chemical abundance pattern (Pollacco, 1999; Kerber et al., 1999; Asplund et al., 1999; Duerbeck et al., 2000). The evidence has been accumulating that the stellar evolution scenario for V4334 Sgr is that of a final He-shell flash (Iben et al., 1983) which occurs during the advanced central star of PNe (CSPN) phase. However, the final He-flash might occur at different times during the post-AGB evolution which results in important differences in nuclear processing and mixing events. This sometimes confusing detail will be recalled in Sect. 2.

However, the observationally gathered information is more numerous and detailed than can be accommodated by current stellar evolution and nucleosynthesis models. This is in particular true for the abundance patterns recorded by Asplund et al. (1999). The most obvious feature is Sakurai's H-deficiency (massfraction $< 1\%$) which is in accordance with the final He-flash scenario. However, more puzzling is the high abundance of lithium which exceeds the initial solar lithium abundance by $0.5 \ldots 1.0$dex. I will discuss a new nucleosynthesis mode of lithium synthesis in Sect. 3.

Another unresolved property of the evolution of V4334 Sgr is the extremely fast evolutionary pace from the dwarf configuration of a CSPN back to the giant branch. All calculations of the born again phase published so far are incompatible with $\tau_{\mathrm{BA}}(\mathrm{V4334\ Sgr}) \simeq 5\,\mathrm{yr}$[1]. An analysis and solution to this problem will be presented in Sect. 4 and 5.

2. The different flavors of final He-flashes

Thermal pulses (TP) are a well known feature of the AGB evolution (Iben and Renzini, 1983). If a thermal pulse occurs during the CSPN phase the star will return to the AGB (Schönberner, 1979). Depending on the time at which the TP occurs during the post-AGB evolution two cases of interest for V4334 Sgr can be distinguished.

2.1. The LTP case

If the TP occurs during the first part of the post-AGB evolution (the *crossing* of the HRD at constant luminosity) than the H-burning shell is still active and the He-flash convection zone in the intershell which forms during the He-flash is not able to extend mixing into the H-rich envelope. Previous calculations of this *late thermal pulse (LTP)* have shown that the H-rich surface is preserved throughout the born again phase of evolution (Schönberner, 1979) including the second descent from the AGB (e.g. Blöcker 1995). However, recent calculations which included the effect of convective overshoot have revealed that born again stars following a LTP can become H-deficient after they have returned to the AGB (Blöcker, 2000; Herwig, 2000).

The reason for the H-deficiency in the LTP case is a *dredge-up* event comparable to the third dredge-up on the AGB. Here, no additional nucleosynthesis is involved. The surface abundance change is only due

[1] $\tau_{\mathrm{BA}} = t_{\mathrm{AGB2}} - t_{\mathrm{TP}}$, t_{AGB2}: time of arrival at AGB for 2nd time, t_{TP}: time of occurrence of final TP during post-AGB evolution.

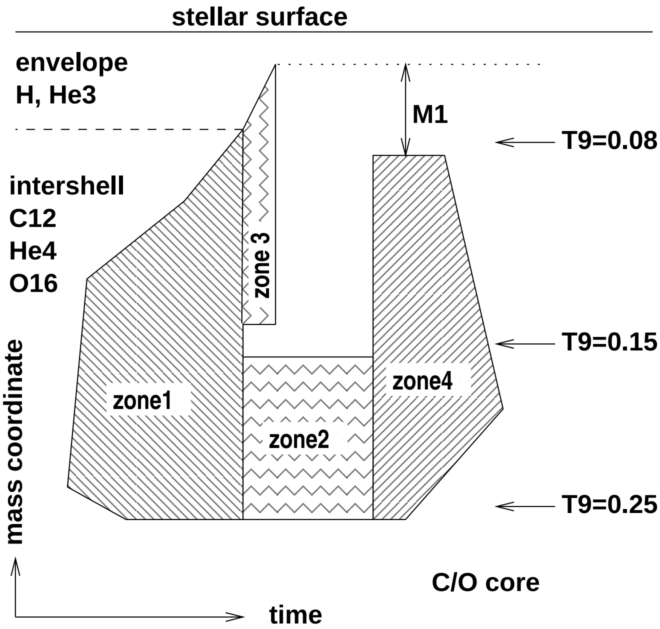

Figure 1. Schematic (not to scale) of the time-evolution of convection zones in the top $0.03\,M_{\odot}$ of a post-AGB star of $0.604\,M_{\odot}$ during a VLTP according to the full evolutionary calculations by Herwig et al. (1999). All shaded areas indicate convectively unstable zones. Approximate temperatures 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.

to mixing processes. The time scale of the born again phase of stellar evolution $\tau_{\rm BA}$ is of the order of $100 \ldots 200$ yr and therefore not in agreement with V4334 Sgr (see Sect. 4). Nevertheless, this evolutionary scenario predicts a temporary increase of the lithium abundance as the convective envelope forms and penetrates into the layer which contains the H-burning profile (see Fig. 6 in Herwig, 2000). It reaches first the region which had experienced only partial pp-burning and consequently formed a small ^{7}Be pocket. After the H-shell is shut off by the LTP there remains enough time for the ^{7}Be pocket to be transformed into a ^{7}Li pocket by e^- capture. Once the bottom of the convective envelope has passed through the former H-shell and reaches the intershell, the surface abundance becomes H-deficient. Clearly this scenario is not suitable for Sakurai's object because it predicts the lithium rich phase while the star is still H-normal. As the H-abundance decreases by dilution so does the lithium abundance.

It has been speculated whether the lithium abundance in V4334 Sgr can be due to the hot bottom burning (HBB) mechanism which is responsible for the lithium production in massive AGB stars (Sackmann and Boothroyd, 1992). However, this is not possible after a late TP. The HBB requires the bottom of the envelope to reach down into the H-shell. Immediately after a thermal pulse, however, H-burning is inactive due to the expansion of the layer hosting the H-shell caused by the He-flash. HBB can not operate without an active H-shell.

2.2. The VLTP case

The evolutionary origin of V4334 Sgr is a *very late thermal pulse* (VLTP). As the name indicates the TP occurs later during the post-AGB evolution than in the LTP case. The VLTP designates a TP which occurs after the CSPN has evolved around the well known knee of post-AGB evolution and has started its evolution towards the WD track at fading luminosities. At this point the H-burning has stopped and the He-flash convection zone reaches out into the H-rich envelope (see Fig. 2 in Herwig 2000 and Fig. 1). Unprocessed material, most notably hydrogen (and ^{3}He if the progenitor AGB star has not experienced HBB) will be ingested into the active He-flash convection zone. As the protons are mixed inward their nuclear life time against being captured by ^{12}C will decrease as the temperature increases. The peak energy by proton captures of ^{12}C is released where the nuclear time scale has decreased to the order of the convective turn-over time scale. In the model by Herwig et al. 1999 the main proton capture location reaches a temperature of $T_8 \sim 1.6$ which can be considered a typical He-burning temperature.

The additional energy release about $0.01\,\mathrm{M}_\odot$ below the stellar surface leads to a short period of enhanced convective instability which is capable of rendering the entire outer layer homogeneous (see Fig. 5 in Herwig et al. 1999) and thus creating a H-deficient post-AGB star by mixing *and* burning processes. Special effort has been made in order to achieve a consistent description of the fast hydrogen burning at high temperatures.

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 convective 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.

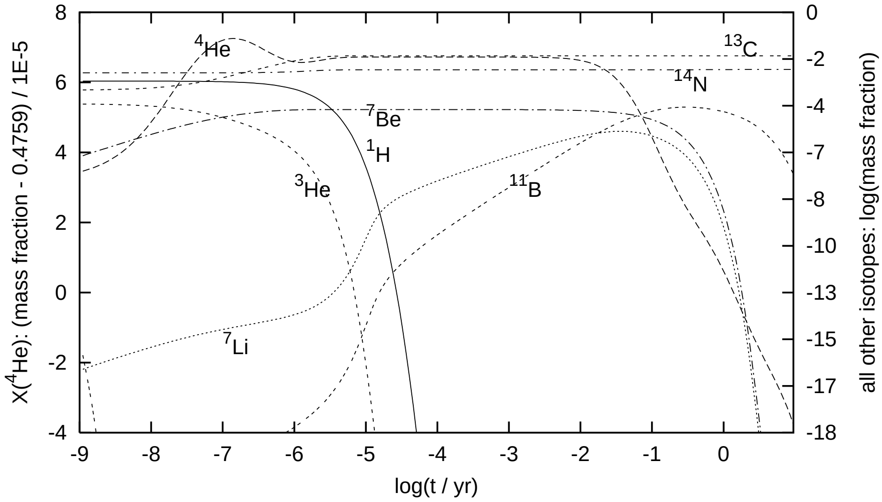

Figure 2. Time evolution of isotopic abundances for constant temperature $T_8 = 1.5$ and density $\rho = 1000\mathrm{g/cm}^3$. The initial abundances resemble the AGB envelope composition ($\log X(^3\mathrm{He}) = -3.9$) with modifications: ^{4}He, ^{12}C and ^{16}O have the intershell abundance of AGB models with overshoot (0.47/0.40/0.11) and the initial hydrogen abundance has been chosen as $\log X(\mathrm{H}) = -3$ to account for the dilution effect of the mixing (all abundances are given as mass fractions).

3. Lithium formation during a VLTP

The large lithium abundance found in V4334 Sgr must be produced within the preceding events the VLTP. The lithium can not be inherited from a previous evolutionary phases. Lithium is destroyed during the giant evolution and produced only during HBB of massive AGB stars. However, even then lithium is expected to be destroyed towards the end of the AGB evolution because the ^{3}He reservoir in the envelope is used up. Finally, the observations reported by Asplund et al. (1999) show an increase of the lithium abundance during the born again evolution while the hydrogen abundance is already very low. That means that a profile of lithium must have existed below the surface in a region were material has been already processing hydrogen. In other words, lithium must have been produced during the actual VLTP.

The convective hydrogen burning is characterized by the formation of a shortlived convection zone which reaches from the location of the maximum H-burning energy generation up to the outermost layers of the star (zone 3 in Fig. 1). It is separated from the main He-flash convection zone (zone 2 in Fig. 1) by a tiny radiative layer which is more or less permeable, depending on the assumptions of overshoot mixing

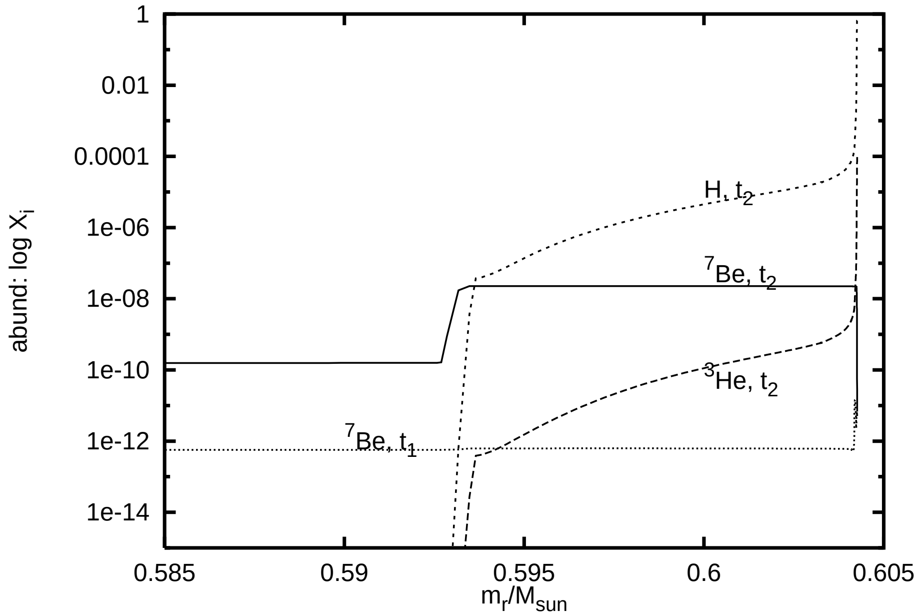

Figure 3. Profiles taken from a coupled convective mixing and nuclear burning model sequence of H- and ^{3}He-ingestion into the He-flash convection zone. $t_1 = 9.6$d $t_2 = 12.7$d after start of envelope ingestion.

between these two layers. In the conditions which prevail in zone 3, lithium may be produced by a new nuclear mechanism of *hot H-deficient* ^{3}*He burning* (Herwig and Langer, 2000). ^{3}He from the envelope reacts with ^{4}He as it enters the hot He-flash convection zone and forms ^{7}Be. During the normal operation of the H-shell any ^{7}Be or possible ^{7}Li produced this way has only a very short lifetime against proton capture. However the situation is different here because the abundance ratio of protons to ^{12}C is reversed. Hydrogen is the most abundant element in the upper part of the H-shell. Protons which are injected in the He-flash convection zone are only a tiny fraction compared to the dominating ^{12}C isotopes. The protons are faster captured by ^{12}C than ^{7}Be is formed from ^{3}He and ^{4}He.

A one-zone nuclear reaction network model sequence is shown in Fig. 2. The initial parameters have been chosen in order to represent the conditions at the bottom of zone 3 (Fig. 1). The nuclear network has been extended by the isotope ^{11}B and α-capture reactions of ^{7}Be, ^{7}Li and ^{7}Be as well as the p-capture of ^{7}Be. These reactions have been identified to be important if ^{3}He is ingested into He-burning. Initially, excess ^{3}He is burned by the pp-I chain reaction which causes the small

^{4}He bump at $\log t/\mathrm{yr} \sim -7$. When the ^{3}He mass fraction falls below a certain value (here $\sim 10^{-5}$) ^{7}Be formation starts because the lower reaction rate of the pp-II reaction is now counterbalanced by the ^{4}He abundance being much larger than the ^{3}He abundance. At this point the time scale of ^{3}He against α-capture is $\tau_\alpha(^3\mathrm{He}) \sim 17$s whereas $\tau_{^{12}C}(\mathrm{p}) \sim 37$s. Thus the protons which are mixed into the He-flash convection zone together with ^{3}He are much faster absorbed by ^{12}C than ^{7}Be can form. By the time ^{7}Be has been produced from the ^{3}He left over after the initial $^3\mathrm{He} +^3 \mathrm{He}$ - burning (pp-I) the hydrogen abundance has been reduced to a negligible value.

^{7}Be has time to be transformed into ^{7}Li by e$^-$-capture and the lithium abundance reaches a mass fraction of $\sim 10^{-6}$ at $\log t/\mathrm{yr} \lesssim -1$. Of course this lithium mass fraction is based on the initial assumptions for abundances and temperature for this one-zone model. It can not be compared directly with the observed lithium abundance of Sakurai's object. Tests with different temperatures have shown that in a hotter regime ($T_8 \gtrsim 2$) the time scale of α-capture on ^{7}Li is smaller than that of e$^-$ capture by ^{7}Be. No significant lithium abundance can build up in this case because any e$^-$-capture is almost immediately followed by an α-capture. For much smaller temperatures ($T_8 \lesssim 0.8$) $\tau_{^7\mathrm{Be}}(\mathrm{p}) < \tau_{^{12}\mathrm{C}}(\mathrm{p})$ and protons are not efficiently captured by ^{12}C but instead destroy ^{7}Be.

The one-zone model described above gives only a limited approximation of the turbulent conditions of ^{3}He-burning in the He-flash convection zone. I have therefore created a preliminary coupled mixing and nucleosynthesis model of the significant stellar layers. The initial condition, including the efficiency of convective mixing, has been chosen according to the VLTP model by Herwig et al. (1999) just before the He-flash convection zone reaches the envelope. The time-evolution of the chemical species has been followed with a diffusion equation for mixing solved fully implicit and simultaneously with the nuclear network equations. The upper boundary of the He-flash convection zone has been shifted outward and into the envelope at a rate of $\dot{M} = 10^{-3}\,\mathrm{M}_\odot/\,\mathrm{yr}$. Selected profiles of light elements are shown in Fig. 3. During the first phase of envelope ingestion until $t_2 = 9.6$d any ^{7}Be which forms is destroyed immediately at the bottom of the He-flash convection zone because the split has not yet formed. At t_2 this split is introduced and thereafter ^{7}Be survives and will eventually form lithium. It appears that this mode of lithium formation is currently the only conceivable way to explain the large lithium abundance in Sakurai's object.

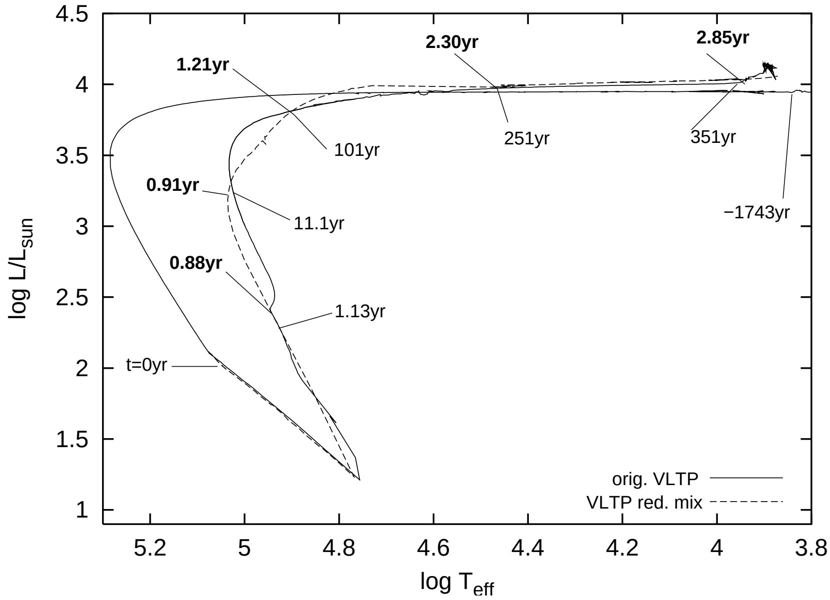

Figure 4. Hertzsprung-Russell diagram of the VLTP sequenz of Herwig et al. (1999) (solid line and time labels to the bottom and right of track) and a recomputation of the flash and subsequent born again evolution under the assumption of significantly reduced mixing efficiency of elements (dashed line starting at $t = 0\,\mathrm{yr}$ and bold time labels to the left and top of the track).

4. The time scale problem

Apparently V4334 Sgr has evolved within only a few years from pre-white dwarf stage to its present state as a luminous and cool giant (Jacoby et al., 1998). This is impossible to reconcile with time scales for the born again evolution found in stellar evolution models published so far.

Two different kinds of models have been constructed. Most models are those of a *late thermal pulse* evolutionary channel. Here the thermal pulse occurs while the star is still on the horizontal crossing from the AGB to the CSPN phase at constant luminosity. During this first post-AGB phase the H-shell is still active and prevents the mixing of envelope material into the He-flash convection zone during the thermal pulse. The star, however, is thrown back to the AGB regime due to the huge energy release of the He-shell as a consequence of the thermal pulse. For these LTP models τ_{BA} is about $100 \ldots 200\,\mathrm{yr}$ (Blöcker, 1995) and thus clearly in disagreement with Sakurai's object (Sect. 2.1).

The other group of computations has simulated the actual VLTP case in which the H-burning has stopped and the protons in the envelope are mixed down into the He-flash convection zone where they burn on the convective time scale. The physical situation of simultaneous burning and convective mixing on the same time scale at the same location requires a special numerical treatment. In view of this problem Iben et al. (1983) have presented a model calculation of the VLTP where they have ignored the nuclear energy released by proton captures in the He-flash zone in order to follow the hydrostatic structure evolution. Therefore their model resembles more that of the LTP as far as nuclear energy production is concerned. They found $140 < \tau_{\mathrm{BA}}/\,\mathrm{yr} < 637$ (from their Fig. 1) which is of the same order of magnitude than the LTP born again evolution. The next computation of the VLTP has been presented by Iben and MacDonald (1995). In that computation $\tau_{\mathrm{BA}} = 17\,\mathrm{yr}$, which is much closer to the born again time scale of V4334 Sgr, although still too large by a factor of $3 \ldots 4$. Unfortunately the modelling techniques and physical assumptions are not discussed in much detail in this short conference paper and the reason for the different values in τ_{BA} compared to the earlier model is unknown.

The model sequence of the VLTP by Herwig et al. (1999) has been described in Sect. 2.2 and as explained the nuclear energy generation by proton captures in the He-flash convection zone has been fully taken into account. However, for this sequence we found $\tau_{\mathrm{BA}} \sim 350\,\mathrm{yr}$, somewhat longer than the LTP case derived from the same AGB starting model. Therefore, this model is not in agreement with V4334 Sgr.

In order to resolve this problem it has been suggested that V4334 Sgr might be very massive. Blöcker (1995) finds that the evolution from a LTP back to the AGB takes 290 yr for the $0.625\,\mathrm{M}_\odot$ model and only 53 yr for the $0.836\,\mathrm{M}_\odot$ model sequence. Thus, CSPNe with larger core masses have a shorter born again phase (Blöcker and Schönberner, 1997). This has lead Duerbeck et al. (2000) to the conclusion that V4334 Sgr could be as massive as $1.0\,\mathrm{M}_\odot$. Moreover they note that a high mass would require the long distance scale ($d \simeq 5.4\,\mathrm{kpc}$) which is in contradiction to the much shorter distance of $d \simeq 1.1\,\mathrm{kpc}$ obtained from the extinction method (Kimeswenger and Kerber, 1998). This high mass might resolve the time scale problem, however, there is good reason against this solution.[2]

[2] Jacoby et al. 1998 have tentatively estimated distances for V4334 Sgr from nebular expansion velocity and diameter together with ages from stellar models by Blöcker (1995) which suggests that more massive models should result in smaller distances. However, taking PN ages as the crossing time from the Blöcker models implictly assumes that the CSPN experiences a LTP. Thus, the Blöcker models, like any LTP models, are not applicable to this case. In fact the LTP can statistically

As discussed in Sect. 3 the high amount of lithium found in V4334 Sgr is not inherited from ap revious stellar evolution phase but must have been synthesized after the star left the AGB for the first time. However, any stellar nucleosynthesis being capable of producing lithium relies on a reservoir of ^{3}He. If V4334 Sgr has a lower core mass than $\sim 0.7\,\mathrm{M}_\odot$ then ^{3}He, built up during the main sequence evolution, will be preserved in the remaining small envelope mass of the post-AGB star and the synthesis of lithium via the above described process is possible. If on the other hand the progenitor of V4334 Sgr has been as massive as required to resolve the time scale problem than the progenitor AGB star would have experienced Hot Bottom Burning which destroys ^{3}He in order to produce ^{7}Li (which is itself destroyed later on when the ^{3}He reservoir of the envelope is consumed). In that case it is hard to imagine how lithium could have been produced during the post-AGB phase without ^{3}He. A very high mass of V4334 Sgr is unlikely for another reason. The abundance ratio N/O in the PN is well below unity (Pollacco, 1999). The PN material reflects the envelope composition during the very last thermal pulses on the AGB. According to recent stellar evolution calculations by Lattanzio & Forestini (1999) AGB stars with the highest mass have a continuously increasing N/O ratio due to Hot Bottom Burning and eventually the ratio exceeds unity, e.g. for the $M_{\mathrm{ZAMS}} = 6\,\mathrm{M}_\odot$ model of solar metalicity. Therefore the progenitor of V4334 Sgr was not an AGB with the highest mass. Instead the progenitor mass was small enough to avoid the Hot Bottom Burning phase alltogether and the time scale discrepancy remains.

5. The solution of the time scale problem

The rapid return of V4334 Sgr to the AGB is another case of the general problem of why stars become red giants. As discussed in detail by Sugimoto and Fujimoto (2000) multiple solutions to stars of similar composition correspond to different topologies of the non-linear stellar structure equations as a boundary value problem. The transition between solutions of different topologies can be obtained if the assumption

occur at any time during the crossing in the case of the LTP and thus the PN age of a born again AGB star following the LTP has no unique relation with the mass. Furthermore, more massive CSPN of the VLTP variety do not necessarily have smaller PN ages. The VLTP occurs typically at $\log L/\mathrm{L}_\odot \lesssim 2$. Blöcker (1995) has shown that massive pre-white dwarfs actually cool down slower than their less massive counterparts. PN ages of massive VLTP born again stars might very well be effected by this cooling behaviour. This means in summary: (a) PN ages of LTP model stars are not applicape to V4334 Sgr and (b) the PN ages of VLTP stars do not necessarily scale down with increasing mass.

of thermal equilibrium is relaxed which leads to the initial value problem of stellar evolution. E.g., in order to switch from a dwarf structure to a giant structure the entropy of the envelope has to be increased.

In the VLTP model by Herwig et al. (1999) the main proton-capture energy is released deep in the He-flash convection zone were the temperature has already been largely increased by the ongoing He-flash. Thus the entropy increase in this layers by the additional H-burning luminosity is barely effecting the outermost layers, and the born again evolution proceeds on the time scale determined by the energy release of the He-flash. Therefore the born again time scale of this VLTP model is similar to that of the corresponding LTP model.

The position of the peak proton-capture energy release is controlled by the velocity of convective element mixing and the rate of proton capture by ^{12}C. The convective velocity defines a time scale of element mixing $\tau_{\rm mix}$ while the p-capture rate defines a nuclear time scale $\tau_{\rm nuc}$. The latter decreases with increasing temperature. As protons are caught by the convective mixing of the He-flash zone they are transported inward on the time scale $\tau_{\rm mix}$ while $\tau_{\rm nuc}$ decreases as they reach the hotter layers. At the position in the He-flash convection zone where both time scales are equal the peak p-capture energy is released. For the VLTP model by Herwig et al. (1999) this position is at mass coordinate $m_{\rm r} = 0.5950\,{\rm M}_\odot$.

In order to release the entropy generated from the additional p-captures into the envelope the position of this energy release must occur further outwards and closer to the original lower envelope boundary. This can be achieved by assuming that the efficiency of element mixing in the He-flash convection zone is *lower*. Then, $\tau_{\rm mix}$ is larger and equals $\tau_{\rm nuc}$ already at a lower temperature at a larger mass coordinate.

I have computed a new VLTP model sequence with a starting model of the original sequence just before the ingestion of protons into the He-flash convection zone starts. The diffusion coefficient which is used to describe the element mixing efficiency according to the mixing-length theory in a time-dependent way has been decreased by a factor of 1000. As a result the peak p-capture energy is released at $m_{\rm r} = 0.6015\,{\rm M}_\odot$ leading to a peak temperature of $T_8 = 1.15$. The evolutionary track of this model sequence is shown in Fig. 4 together with the original VLTP sequence and both equipped with time marks. The evolution back to the AGB is greatly accelerated and complete within $\sim 3\,$yr. Thus, the evolutionary time scale of the VLTP model with reduced efficiency of element mixing is in full agreement with that of V4334 Sgr. Tests have indicated that these modified models are as well a suitable host for the *hot H-deficient* ^{3}He-*burning* described in Sect. 3.

This result appears to demonstrate that the convective velocities obtained from the mixing-length theory are not a particular good estimate. In fact, Sakurai's object may be used in the future to test convection theory.

Acknowledgements

This work has been supported in part by the *Deutsche Forschungsgemeinschaft, DFG* (La 587/16). I would like to thank N. Langer and D.A. VandenBerg for very useful discussions.

References

Asplund, M., D. L. Lambert, T. Kipper, D. Pollacco, and M. D. Shetrone: 1999, 'The rapid evolution of the born-again giant Sakurai's object'. *A&A* **343**, 507–518.

Blöcker, T.: 1995, 'Stellar evolution of low and intermediate mass stars. II. Post-AGB evolution'. *A&A* **299**, 755.

Blöcker, T.: 2000, 'Stellar evolution on the AGB and beyound'. In: T. Blöcker, R. Waters, and B. Zijlstra (eds.): *Low mass Wolf-Rayet Stars: origin and evolution.* in press.

Blöcker, T. and D. Schönberner: 1997, 'Stellar evolution of low and intermediate-mass stars III. An application of evolutionary post-AGB models: the variable central star FG Sagittae'. *A&A* **324**, 991.

Duerbeck, H. W., W. Liller, and S. B. etal.: 2000, '"The rise and fall of V4334 Sagittarii (Sakurais Object)"'. *AJ* **119**, 2360–2375.

Herwig, F.: 2000, 'Internal mixing and surface abundances of [WC] CSPN'. In: T. Blöcker, R. Waters, and B. Zijlstra (eds.): *Low mass Wolf-Rayet Stars: origin and evolution.* in press, astro-ph/9912353.

Herwig, F., T. Blöcker, N. Langer, and T. Driebe: 1999, 'On the origin of hydrogen-deficient post-AGB stars'. *A&A* **349**, L5.

Herwig, F. and N. Langer: 2000, 'Convective proton and ^{3}He ingestion into helium burning: Nucleosynthesis during a Post-AGB thermal pulse'. *Nucl. Phys. A* p. in press. astro-ph/0010120.

Iben, Jr., I., J. B. Kaler, J. W. Truran, and A. Renzini: 1983, 'On the evolution of those nuclei of planetary nebulae that experience a final helium shell flash'. *ApJ* **264**, 605.

Iben, Jr., I. and J. MacDonald: 1995, 'The Born Again AGB phenomenon'. In: D. Koester and K. Werner (eds.): *White Dwarfs.* Heidelberg, p. 48, Springer.

Iben, Jr., I. and A. Renzini: 1983, 'Asymptotic Giant Branch evolution and beyond'. *ARA&A* **21**, 271.

Jacoby, G. H., O. De Marco, and D. G. Sawyer: 1998, 'The Size and Age of Sakurai's Planetary Nebula and the Temperature of it's Central Star'. *AJ* **116**, 1367.

Kerber, F., J. Köppen, M. Roth, and S. Trager: 1999, 'The hidden past of Sakurai's object'. *A&A* **344**, L79.

Kimeswenger, S. and F. Kerber: 1998, 'The distance of Sakurai's Object'. *A&A* **330**, L41.

Lattanzio, J. and M. Forestini: 1999, 'Nucleosynthesis in AGB stars'. In: T. L. Bertre, A. Lebre, and C. Waelkens (eds.): *AGB Stars*. p. 31, ASP.

Pollacco, D.: 1999, 'The planetary nebula surrounding the final thermal pulse object V4334 Sagittarii'. *MNRAS* **304**, 127–134.

Sackmann, I.-J. and A. I. Boothroyd: 1992, 'The Creation of Superrich Lithium Giants'. *ApJ* **392**, L71.

Schönberner, D.: 1979, 'Asymptotic Giant Branch Evolution with Steady Mass Loss'. *A&A* **79**, 108.

Sugimoto, D. and M. Y. Fujimoto: 2000, 'Why stars become red giants'. *ApJ* **538**, 837.