Mem. S.A.It. Suppl. Vol. 22, 247

Memorie della
Supplementi

Lithium production in SAGB stars

Herbert H.B. Lau[1,2], Carolyn L. Doherty[2], Pilar Gil-Pons[3,2], and John C. Lattanzio[2]

[1] Argelander Institute for Astronomy, University of Bonn, Auf dem Huegel 71, D-53121 Bonn, Germany, e-mail: `hblau@astro.uni-bonn.de`
[2] Centre for Stellar and Planetary Astrophysics, School of Mathematical Sciences, Monash University, Victoria 3800, Australia
[3] Department de Fisica Aplicada, Universitat Politecnica de Catalunya, Barcelona, Spain

Abstract. We explore the production of and stellar yields of 7Li for a range of mass and metallicity. We test the effect of varying the mass loss rate and well as the mixing length parameter on the production of lithium. There is a short duration of strong enhancement of Lithium in the early AGB phase, before any thermal pulses. Higher mass-loss rate, particularly in the early AGB phase, will result in stronger Li enhancement. In general, metal-poor stars produce less lithium because the mass-loss rates are lower during the Li-rich phase. We also compare the observed abundances of Li-rich stars with our models and discuss possible formation of Li-rich stars through mass transfer from SAGB primary. If a SAGB star is observed before thermal pulses or the SAGB primary evolution truncated before thermal pulses due to binary interactions, then the observed SAGB stars or its companion may be observed as Li-rich but without *s*-process isotopes.

Key words. Stars: AGB and post-AGB –evolution –binaries

1. Introduction

Super asymptotic giant branch (SAGB) stars ignite carbon in the early AGB phase. They develop ONe cores, but the cores are not hot enough for further nuclear reactions. The typical mass range is around $7-10M_{\odot}$, with the exact boundary depending on the initial metallicity and the treatment of convection. Compared to low-mass AGB stars, the thermal pulses are weaker with a shorter interpulse period. Also, the intershell convective zone is smaller and is on the order of $5 \times 10^4 M_{\odot}$.

Typically after second dredge up, the temperature at the bottom of the convective envelope is hotter than 60 million K. Lithium is produced during hot bottom burning in the early phases of the AGB via Cameron & Fowler (1971) mechanism. ^{7}Be is produced through the reaction ^{3}He + ^{4}He$-$ $>$ ^{7}Be , and is then converted into ^{7}Li by electron capture (^{7}Be $+^{-}$ e$-$ $>$ ^{7}Li) . Lithium produced is then rapidly transported to the surface by convection, and hence there is a short period of time in which Li is strongly enhanced in the surface, typically by more than 1 order of magnitude. However, lithium is subsequently destroyed by proton capture, i.e. ^{7}Li $+^{1}$ H$-$ $>$ ^{4}He + ^{4}He . Furthermore, the production of lithium is reduced when ^{3}He is depleted, and so the surface abundance of lithium decreases after an initial peak. In this work, we discuss the effect of metallicity, mixing length parameter, and in particular, the adopted mass rates on the yield of lithium from SAGB stars. A high mass loss rate during the Li-enriched period will significantly increase the yield. Also a companion star within a suitable range of separation can accrete materials significantly enhanced in lithium. We compare the observed abundances of a couple lithium-rich stars with our models and discuss whether they could be a SAGB star or companion to a SAGB star or massive AGB star. Ventura & D'Antona (2010) has also studied lithium production in massive AGB and SAGB stars for metallicity $Z = 10^{-3}$ and their results will also be compared with our work.

2. Method

We use the Monash stellar evolution code MONSTAR to study the evolution of super asymptotic giant branch (SAGB) stars. An extensive set of SAGB evolutionary models computed with this code can be found in Doherty et al. (2010). The numerical problems and detailed description of evolution during the thermal pulsating AGB phases (TPAGB) can be found in Lau et al. (2012). In most of the models AGB massloss rate is calculated based on Vassiliadis & Wood (1993). Other mass loss rates, such as Bloecker (1995)($\eta = 0.1$), van Loon et al. (2005) and Reimers (1975)($\eta = 0.5$) are also used to study the effect of mass loss on nucleosynthesis yield. The mixing length parameter is set to 1.75. Other mixing length parameters are also used to investigate how treatment of convection affects the surface lithium abundances. We do not adopt any convective overshooting or extra mixing, such as cool bottom process. The initial Lithium abundance A(Li) is set to be scaled with solar abundances, i.e. [Li/Fe] = 0, for solar, LMC, SMC metallicitiy. For lower metallicity model, we adopt A(Li)=2.176, representatve of the Spite Pleateau value (Spite & Spite 1982).

Nucleosynthesis calculations for minor isotopes, such as Li, were performed using the post processing program MONSOON (Church et al. 2009), with nuclear network used comprises of 77 nucleosynthetic species up to and including the iron group elements. The yield of Li is shown as the value of log ($< \mathrm{Li} > / \mathrm{Li_o}$), where $< X >$ is the average value of lithium ejected during the whole evolution and $\mathrm{Li_o}$ is the initial abundances of lithium.The total lithium ejected is calculated by multiplying the instantaneous lithium surface composition with the instantaneous mass-loss rate throughout the whole evolution, and the average lithium composition for the ejecta is the total amount of lithium ejected divided by the total mass ejected, typically the value of the convective envelope. The yield can be considered as the enhancement factor of lithium due to nuclear reactions.

3. Result

In all our models, Li is enriched at the surface for a brief period of time in the early TP-SAGB before the first thermal pulses. The peak abundances of lithium A(Li) can be as high as 4.3 (see fig.1). For the same metallicity, the Li yield is higher for higher initial mass (fig.2. More massive SAGB stars produce a stronger peak of surface Li abundances because temperatures in the base of their convective envelopes are much higher, resulting a more rapid production of Li. The mass loss rate is also higher for massive AGB stars so more Li is extracted when it is strongly enhanced in the surface. In fact, Li yields are highly dependent on the mass-loss rates. The faster mass loss rate, such as the presciption by Bloecker (1995) results in much higher lithium yield because the whole envelope is lost when lithium is strongly enhanced in the surface. For slower mass-loss rates such as the prescription by Reimers (1975), only a small fraction of the lithium produced during the peak is lost from the star through mass loss, and the ejecta from the star changes from Li-rich to Li-depleted throughout the evolution (fig.3). Different mass-loss prescriptions adopted can change the Li yield by more than 1 order of magnitude .

Ventura & D'Antona (2010) has discussed lithium yield in SAGB models for metallicity $Z = 10^{-3}$. We do not have a full grid of models at the metallicity yet, but we find that the average lithium abundance in the ejecta of our $7.5 M_{\odot}$ model agree well with their model. The average lithium abundance A(Li) is 3.1 in our models, while A(Li) is 2.9 in their mod-

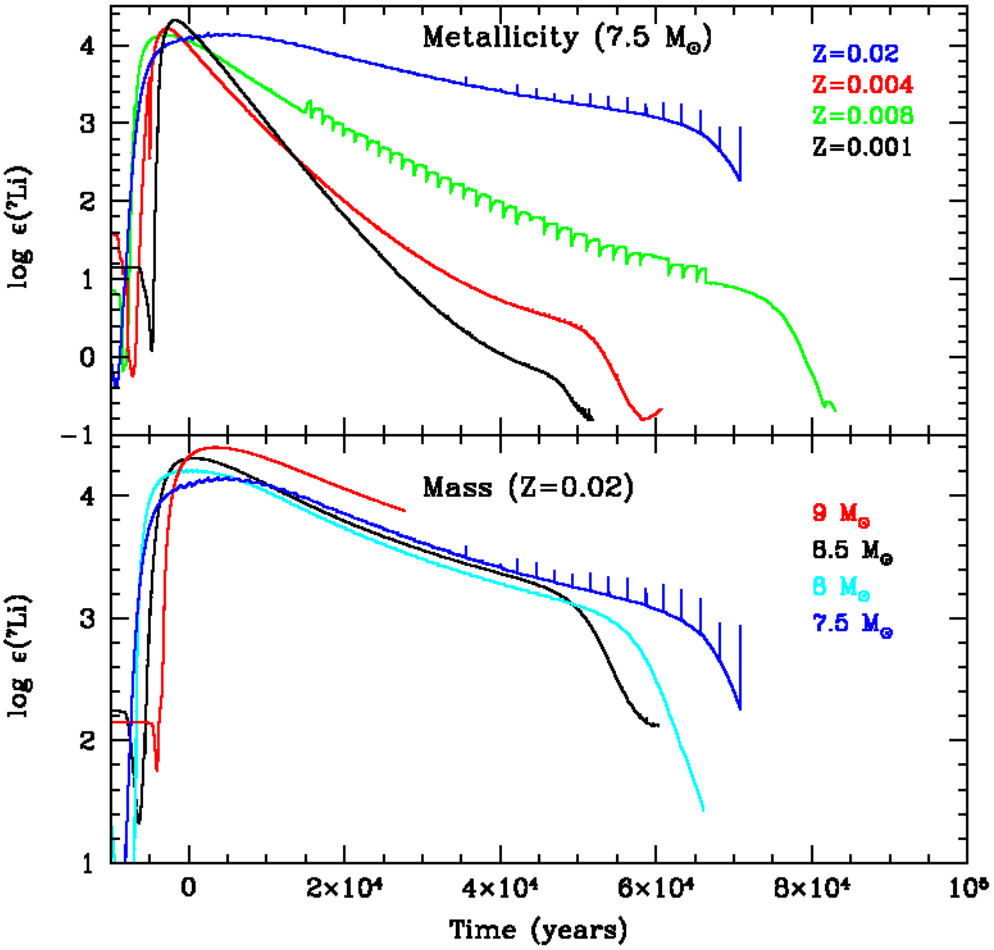

Fig. 1. Evolution of Li surface abundances for various models. Top: 7.5$M_\odot$ models for $Z = 0.02, 0.008, 0.004, 0.001$ (top to bottom). It shows that at lower metallicity, Li is depleted much faster. Bottom: Solar metallicity models for 7.5$M_\odot$ 8$M_\odot$ 8.5$M_\odot$ and9$M_\odot$. The more massive models reach a higher peak of Li. The time are scaled such that at time=0 is roughly when Li is at its peak.

els. However, in our 6.5$M_\odot$ and 7$M_\odot$, our average lithium yield is negative, while in their models the lithium yield is close to zero. This is probably because the mass loss prescription we use (Vassiliadis & Wood 1993)'s is in general slower than that the prescription used by Ventura & D'Antona (2010) (Bloecker 1995).

Increasing mixing length parameter α actually decreases the net yield of Li. Increasing α results in a much larger temperature at the base of convective envelope and leads to faster depletion of lithium. Therefore, while increasing α leads to a slight increase of mass loss rate, the peak lithium value is lower and lithium is depleted much faster, resulting a low yield of lithium (fig.3).

At lower metallicities, the temperatures at the base of the convective envelopes are higher so AGB stars with lower initial masses can produce Li at lower metallicity. For the same

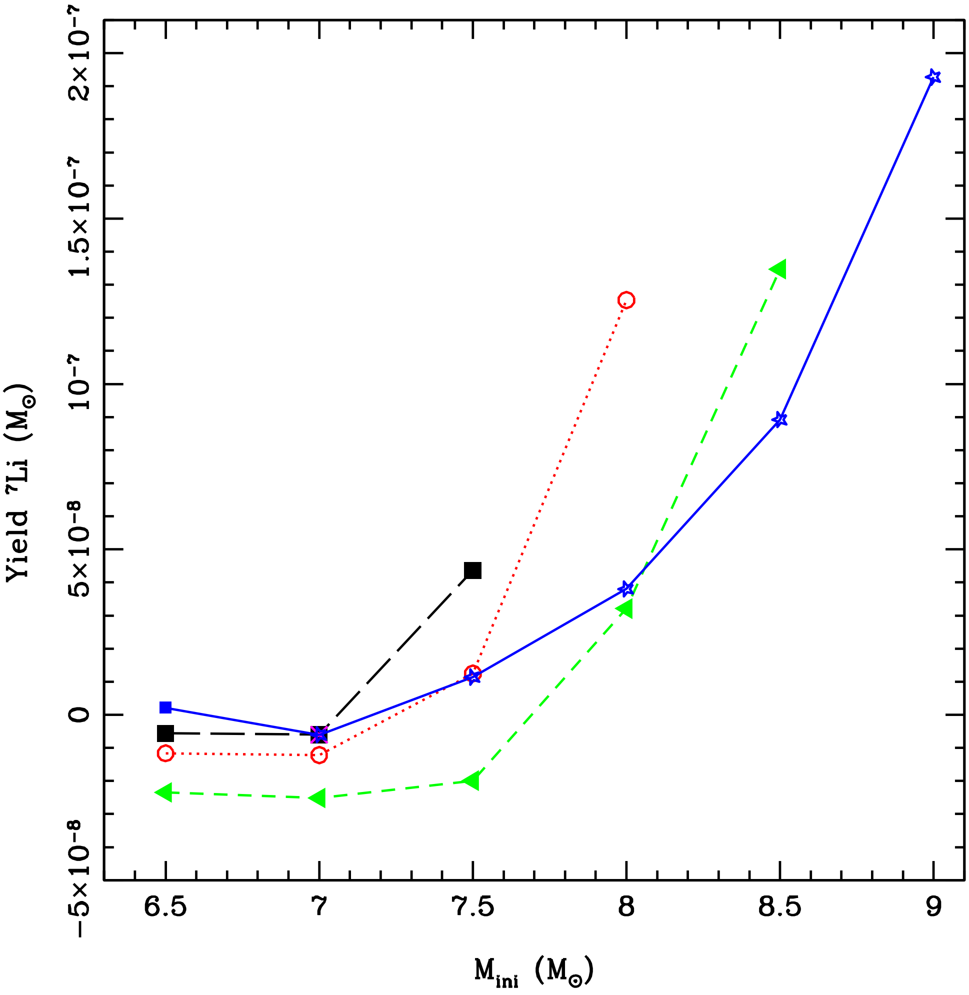

Fig. 2. Li Yield for models at different masses and metallicities. Stars($Z=0.002$), Triangle($Z=0.008$), circle ($Z=0.004$), square($Z=0.001$). Yields for metal rich models tend to give higher yield, but the trend is not uniform among all masses.

initial mass, the peak surface Li abundances is higher at lower metallicity. However, the mass-loss rate is also lower because the stars are much more compact. Therefore, it is much harder to extract lithium before it gets destroyed, and so the Li yield is lower if we adopt the same mass-loss prescription. In general the higher metallicity stars produce more lithium than metal-poor stars. However, the presence of a close companion at suitable separation can strip off the envelope at the early AGB through mass transfer. The companion stars will then accrete materials that is significantly enhanced in Li and any mass lost due to non-conservative mass transfer will also eject Li-rich material. This can be one possible site to produce Lithium, although the actual contribution will strongly dependent on the initial distribution of separation and masses for binaries.

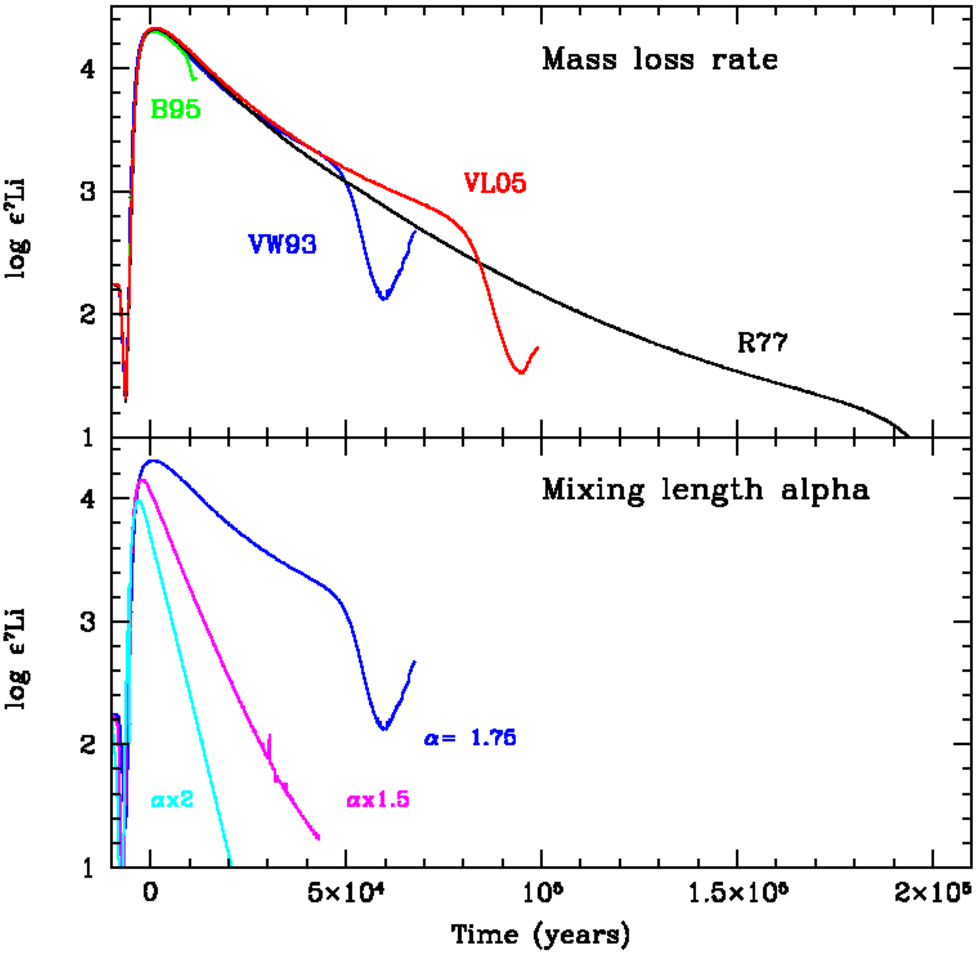

Fig. 3. Evolution of Li abundances for models with different mass loss rate and mixing length parameter. Top: Models for (left to right) Bloecker (1995), Vassiliadis & Wood (1993), van Loon et al. (2005), Reimers (1975). For model with Bloecker (1995) mass loss rate, the whole envelope is lost when Li is still strongly enhanced. Bottom: Models with different mixing length parameter α. (from left to right) $\alpha = 3.5$, $\alpha = 2.625$, $\alpha = 1.75$ (default). Models with higher mixing length parameter clear deplete Li much quicker.

4. Discussion

In our models we find that lithium is significantly enhanced in the early TPAGB phase, typically before any thermal pulses. Therefore, there is a period that the surface composition of the stars are rich in lithium, but not in s-process isotopes (see fig.4. In fact, we expect stars with observed strong Li enhancements, such as R Nor with A(Li)=+4.6 (Uttenthaler et al. 2011), not to be enhanced in s-process isotopes, such as Tc. In that regards, observed abundances of R Nor is consistent with massive AGB/SAGB models just before thermal pulses. On the other hand, AGB stars with significant carbon and s-process enhancement should have lower or no lithium enhancement because most lithium produced have been destroyed. Because the pe-

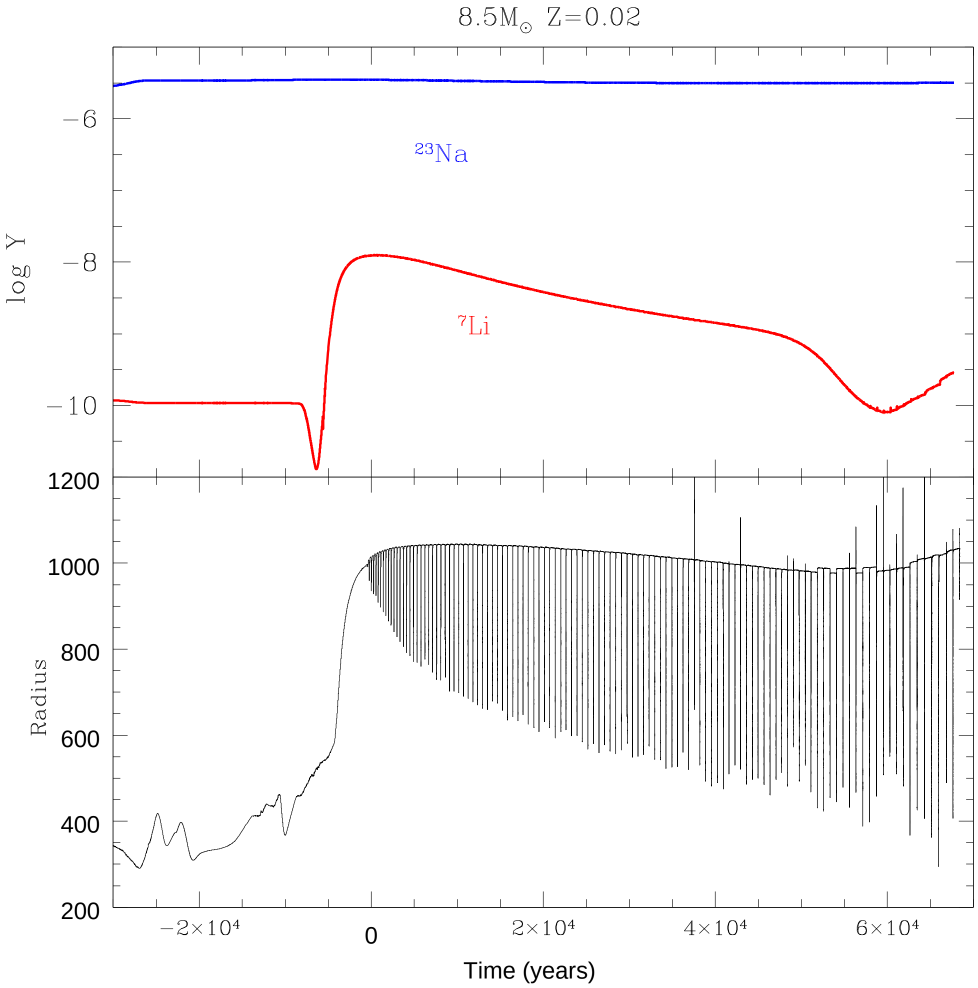

Fig. 4. Top: Surface sodium and lithium evolution with time for $8.5M_\odot$ model at Z = 0.02. Bottom: Radius evolution for the same model. It is clear that the lithium enhancement occurs at the same time when the star is expanding in the AGB phase. In this model, the sodium abundance do not change significantly.

riod for significant Li enhancement is rather short, we should not expect to see many Li-rich AGB stars.

In a binary system, the observed abundances of the companion stars will depend on when and how mass is transferred. The star is rapidly expanding when lithium is enhanced during early AGB phase (see fig.4), so if the primary stars fills the Roche lobe in this period, the whole envelope is then stripped off rapidly and Li-rich materials is transferred onto the companion star. Also, the evolution of the primary AGB star is truncated because the whole envelope is lost before the onset of thermal pulses and hence there is no third dredge-up, and *s*-process or carbon will not be enhanced. As a result, the companion star may only accrete materials enriched in lithium, but not *s*-process isotopes. It may be a possible way to form super-Li-rich turnoff stars, such

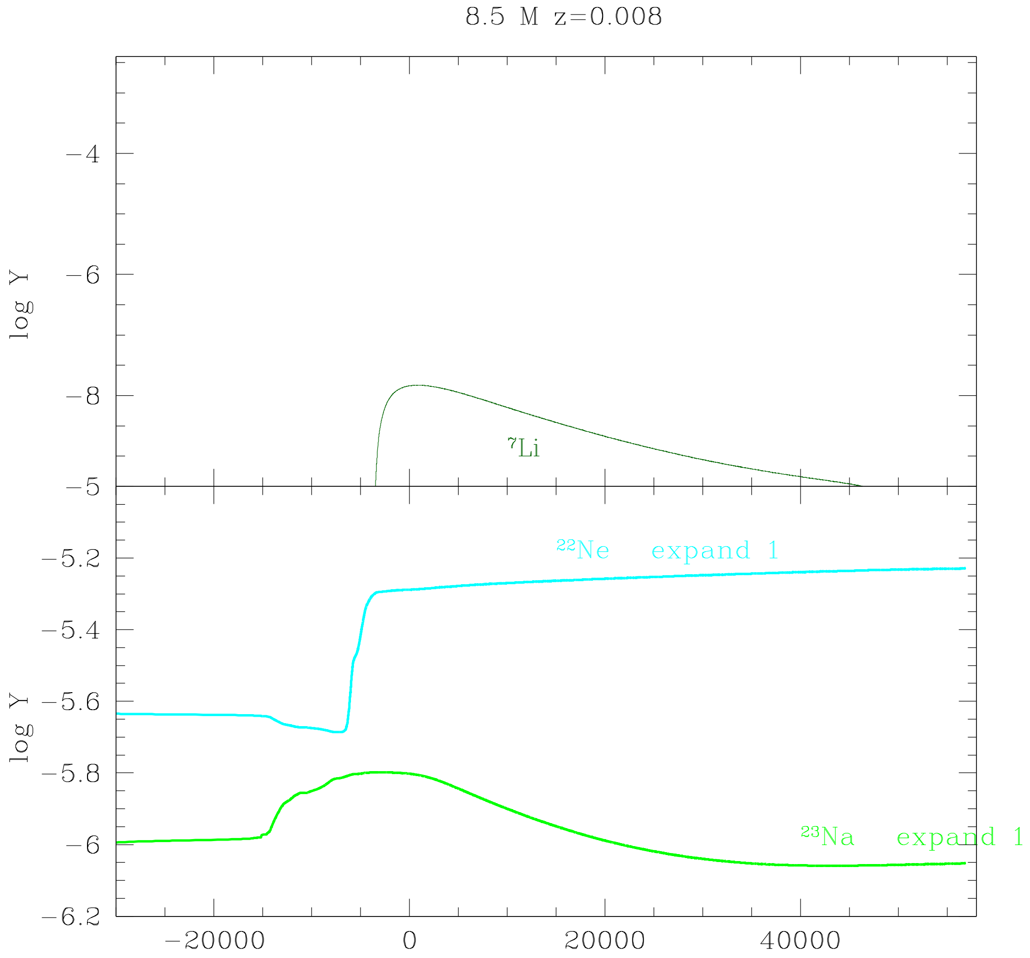

Fig. 5. Top: Surface lithium evolution with time for $8.5 M_\odot$ model at $Z = 0.008$ (x-axis is years). Bottom: Surface neon and sodium evolution with time for $8.5 M_\odot$ model at $Z = 0.008$. In this metallicity, sodium and neon are enhanced roughly at the same time as lithium.

as the one observed by Koch et al. (2011), even though overabundance of *s*-process elements are not observed. Because the primary AGB star have already undergone second dredge up, some elements such as nitrogen should also be enhanced. For example, sodium is enhanced at the same time as lithium (see fig.**??**), although the enhancement is much stronger in low metallicity. Therefore, if such enhancement is not observed, particularly in low metallicity stars, it may potentially rule out the scenario involving AGB companion. Although detailed binary evolutionary models will be required to predict the observed abundances, particularly if other mixing process, such as thermohaline mixing (Stancliffe & Glebbeek 2008), can change the surface composition of the secondary after mass transfer. Nevertheless, the actual frequency of this formation channel can only be determined by a future study of population synthesis of binary systems with massive AGB primaries.

On the other hand, if the system is a bit wider, Roche lobe overflow could be avoided and the companion stars will only accrete materials through the stellar wind from the AGB primary. In this scenario, the evolution is not truncated before third dredge up. Because the companion star accrete materials both during the Li-rich phase and *s*-process isotopes rich phase, the star can be observed as *s*-process isotopes enhanced and carbon enhanced but the Li enhancement will be much weaker.

5. Conclusions

We have calculated a Li yields for SAGB stars with different metallicities. We find that there is a sharp peak of Li enhancement, after 2nd dredge up but before any thermal pulses. Li is then subsequently destroyed. Therefore, the Li yields are strongly dependent on mass-loss rates during the Li-rich period. While fast mass loss rates such as Bloecker (1995) will extract most of the lithium produced because a significant fraction of the envelope is lost, a slower mass-loss rate, such as van Loon et al. (2005), will extract significantly less lithium. The uncertainly in mass-loss prescription used can lead to more than 1 order of magnitude uncertainty in lithium yield prediction. In general more massive AGB stars, such as SAGB stars, give a higher yield in Li because of the stronger mass-loss. Similarly, low metallicity are likely to give lower Li yield because of the lower mass-loss rate.

Because Li yields are highly dependent on the mass loss rates, besides the mass-loss recipe, and uncertainty in input physics that can affect mass-loss rates will subsequently have significant effect on lithium production. For example, in low-metallicity stars, if opacities due to C/O molecules are included in opacity calculation, the mass-loss rates will be much higher at the beginning of the TP-(S)AGB phase. This would favor scenario that metal-poor massive AGB stars can make significant contribution to lithium production. In massive stars and SAGB stars, lithium is strongly enhanced before thermal pulses and third dredge up, it is possible for an AGB star to be observed as Li-rich stars without *s*-process isotopes. Moreover, for a binary system with suitable initial separation, the whole envelope can be lost during the Li-rich phase and the companion stars can accrete materials rich in Li without carbon and *s*-process enhancement. Therefore, an observed stars with strong lithium enhancement without *s*-process does not necessarily rule out the possibility of AGB stars contribution.

Acknowledgements. We would like to thank Prof. Robert Izzard for useful advice on binary system.

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