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Lithium evolution in RGB and AGB stars

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Abstract. Lithium is one of the most fragile elements in the Universe. Such a feature is used by stellar modellers to test the robustness of their evolutionary models. Li is observed on the surface of giant stars, during their ascents to the giant branch. During those phases, its abundance depends on a delicate balance between mixing processes and nuclear burning. In this review we mainly concentrate on processes affecting ^{7}Li nucleosynthesis during the Asymptotic Giant Branch phase of low and intermediate mass stars.

Key words. Stars: abundances – Stars: AGB and post-AGB – Stars: mass-loss – Stars: interiors – Stars: low-mass

1. Introduction

^{7}Li is a very fragile nucleus. In stars, its photospheric abundance can be easily lowered when convective processes bring it to zones where the temperature is high enough to efficiently activate proton captures on ^{7}Li (T > 20 MK; Eq. 1). However, its abundance may increase as soon as ^{7}Be captures an electron, releasing an electronic neutrino (Eq. 2). This weak process largely depends on the temperature and density of the stellar plasma, ranging from approximately 50 days to 1000 years. ^{7}Be is synthesized via the *pp* fusion chain by ^{3}He captures on ^{4}He (Eq. 3), as soon as the temperature exceeds 40 MK . On the other side, beryllium is destroyed by proton captures for T > 80 MK (Eq. 4). In summary, four reaction are at play:

$$^7\mathrm{Li}(p,\alpha)^4\mathrm{He} \qquad (T \sim 20\ \mathrm{MK}) \quad (1)$$

$$^7\mathrm{Be}(e^-,\nu_e)^7\mathrm{Li} \qquad (\tau \sim 50\mathrm{d} \div 1000\mathrm{yr}) \quad (2)$$

$$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be} \qquad (T \sim 40\ \mathrm{MK}) \quad (3)$$

$$^7\mathrm{Be}(p,\gamma)^8\mathrm{B} \qquad (T \sim 80\ \mathrm{MK}) \quad (4)$$

Under radiative conditions (no macroscopic movements of matter), therefore, lithium can only be destroyed. On the other hand, lithium may result enhanced on the surface of giant stars (with respect to the stellar pristine composition). This is made possible by mixing processes, that quickly remove beryllium from hot layers to more external shells, where it may safely decay to lithium.

2. The e$^-$ capture on ^{7}Be

In order to pile up lithium in the external layers, convection (or similar mixing processes) has to deepen enough to produce beryllium (but not too much to destroy it) with the proper efficiency, in order to overwhelm the electron capture on ^{7}Be (see Fig. 1). It is therefore clear that an accurate theoretical model for the ^{7}Be electron-capture in stellar plasma is necessary.

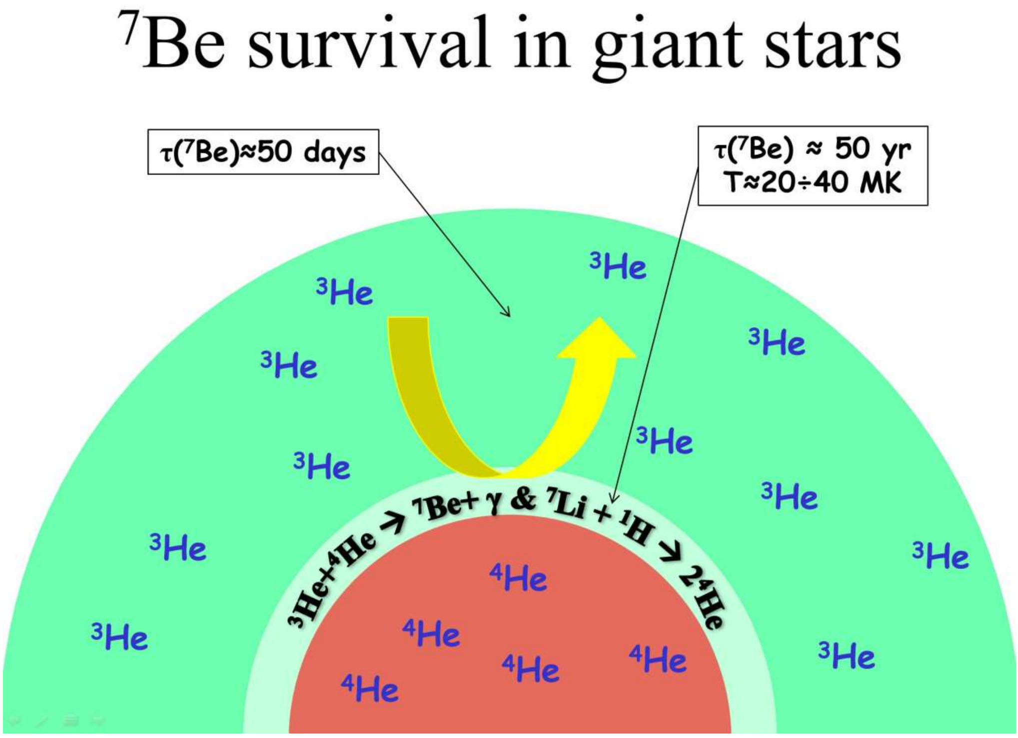

Fig. 1. Scheme of beryllium production/destruction in giant stars.

Unfortunately, we still lack a detailed knowledge of the dependence of this rate from the physical and chemical conditions below the envelope of giant stars. Indeed, extrapolations of this rate valid for the solar core are quite insecure, due to rather different conditions of H-burning environments in evolved stars with respect to the solar one. Those objects, in fact, are characterized by a wide temperature and density ranges. As it can clearly be seen in Fig. 2, the mean lifetime τ for ^{7}Be, which is estimated to be ~ 53 days in laboratory conditions, dramatically changes in stellar environments. Some years ago Simonucci et al. (2013) developed a first principles approach to derive the electron capture rate on ^{7}Be, by modeling it as a two-body scattering process. The effects of the new rate on a Standard Solar Model has been recently presented by Vescovi et al. (2019).

3. The Cameron-Fowler mechanism and low-metallicity low-mass stars

As it is so easy to destroy, ^{7}Li production requires special conditions, which are limited to a few astrophysical scenarios. Among them, there are low and intermediate-mass Asymptotic Giants Branch (AGB) stars. This was proposed in 1971 by Cameron and Fowler (the so-called Cameron & Fowler Mechanism, CFM; Cameron & Fowler 1971)[1]. Since at that epoch complete AGB models were available only for low mass stars (Schwarzschild & Härm 1967; Sanders 1967), the CFM was thought to occur during the AGB phase of those objects, when a large amount of hydrogen is suddenly mixed from the envelope down to very hot layers (T > 100 MK). The fast mixing of beryllium to the surface would

[1] For the sake of discussion, it was initially hypothesized by Cameron (1955).

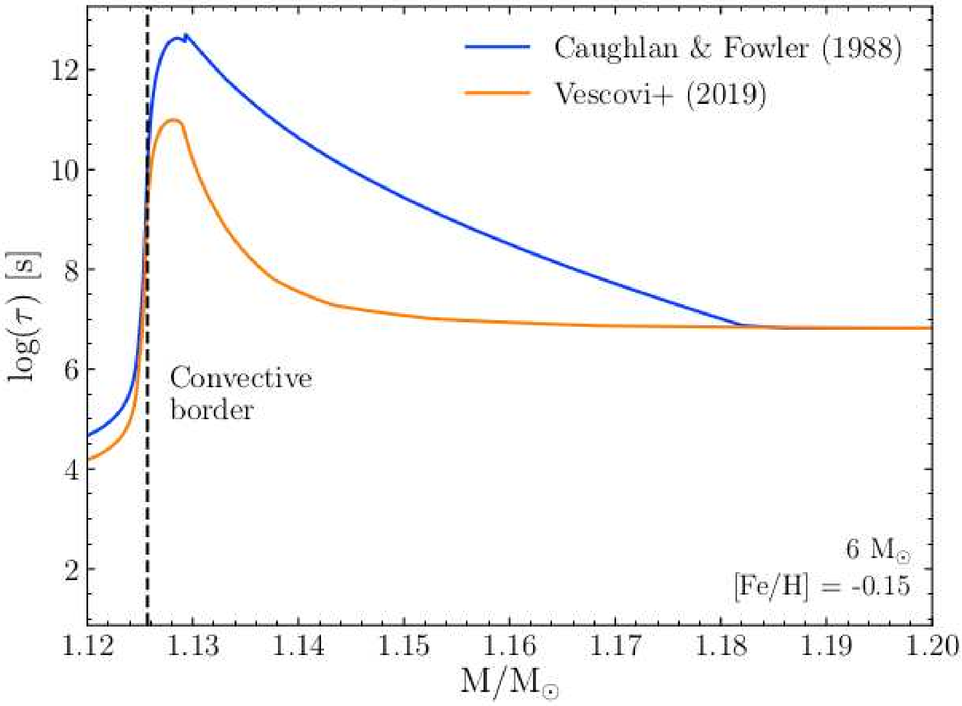

Fig. 2. Electron capture timescale for ^{7}Be in a 6$M_\odot$ AGB star with Fe/H=-0.15, as a function of the mass. Rates are from Caughlan & Fowler (1988) and from Vescovi et al. (2019).

guarantee the survival of lithium in the envelope. Actually, the occurrence of such mixing episodes has been explored in the years by several authors (Hollowell et al. 1990; Fujimoto et al. 2000; Iwamoto et al. 2004; Campbell & Lattanzio 2008). In fact, stellar modelling of low mass metal-poor AGB stars predicts that at the very beginning of the thermally pulsing phase, during the first fully developed thermal pulse (TP), the convective He-shell may ingest some protons from the H-rich envelope. During this Proton Ingestion Episode (PIE), ^{7}Be is rapidly created through the ^{3}He$(\alpha,\gamma)^7$Be reaction but, due to the fast stellar evolution, has no time to undergo electron capture before the occurrence of the subsequent Third-Dredge-Up (TDU). Then it is diluted in the envelope, where it freely decays in ^{7}Li (Cristallo et al. 2009). As a consequence models experiencing PIEs are characterized by a very large production of ^{7}Li, reaching log $\epsilon(^7\mathrm{Li}) \sim 4$ (see Fig. 3). It has to be noticed that the final surface lithium abundance is strictly connected to the amount of ^{3}He in the envelope, which obviously depends on the preceding evolutionary phases.

4. Extra-mixing in low mass giant stars

During the Red Giant Branch (RGB) and the AGB phases, processes responsible for Li-depletion could also be active. Among those processes there is the so-called "Cool Bottom Process" (CBP), which was firstly hypothesized in the 1990s in order to explain oxygen isotopic ratios measured in pre-solar Al_2O_3 grains (Boothroyd et al. 1994, 1995; Wasserburg et al. 1995). In these papers, a two-stream conveyor belt circulation model has

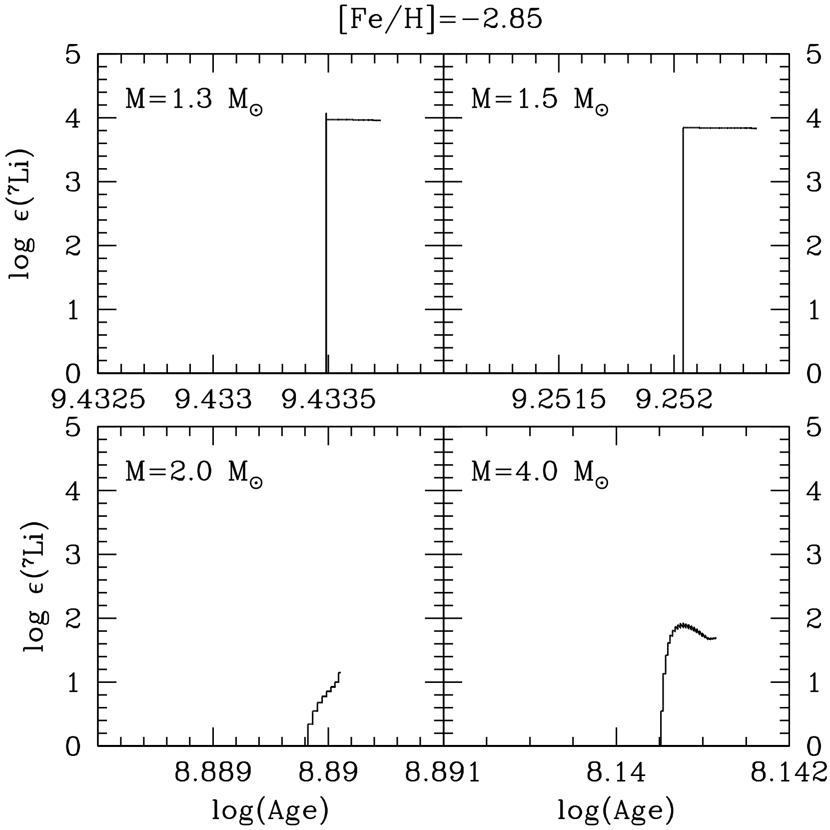

Fig. 3. Variation with time of ^{7}Li surface abundance for 1.3, 1.5, 2.0, and 4.0 $M_{\odot}$ with [Fe/H]=-2.85. Low mass models (upper panel) becomes Li-rich, while more massive models (lower panel) do not.

been postulated, in which an *ad hoc* mixing brings material down to layers hot enough for some nuclear processing. Such a model is characterized by two free parameters: the maximum temperature at which the material is exposed (hence the maximum mass penetration) and the circulation rate within the extra-mixed region. Among the explanations for such a type of mixing, magnetic fields result the most promising candidate (Busso et al. 2007; Nucci, & Busso 2014; Palmerini et al. 2017).

Palmerini et al. (2011) computed detailed CBP models to evaluate its effect during both the giant branches. They found that, during the RGB, CBP does not change Li abundance much. Moreover, in order to reproduce observations, a wide spread, mostly ascribed to the previous evolutionary phases, has to be taken into account. Finally, these authors were not able to fit observations with A(Li)>1.5. Nevertheless, Li-rich giants have been discovered in both the field and in clusters and they appear to represent about 3-5% of all giants (Brown et al. 1989; Balachandran et al. 2000; Reddy & Lambert 2005; Monaco et al. 2011; Kirby et al. 2012; Martell & Shetrone 2013; Adamów et al. 2014; Casey et al. 2016). Recently, Yan et al. (2018) discovered an extremely Li-rich star: TYC429-20971, with A(Li)=4.51. Interestingly, these authors ascribed it to a mixing process with fast rising magnetized tubes and slowly-settling non-magnetized material. In such a case, the destruction of Li by downward settling is af-

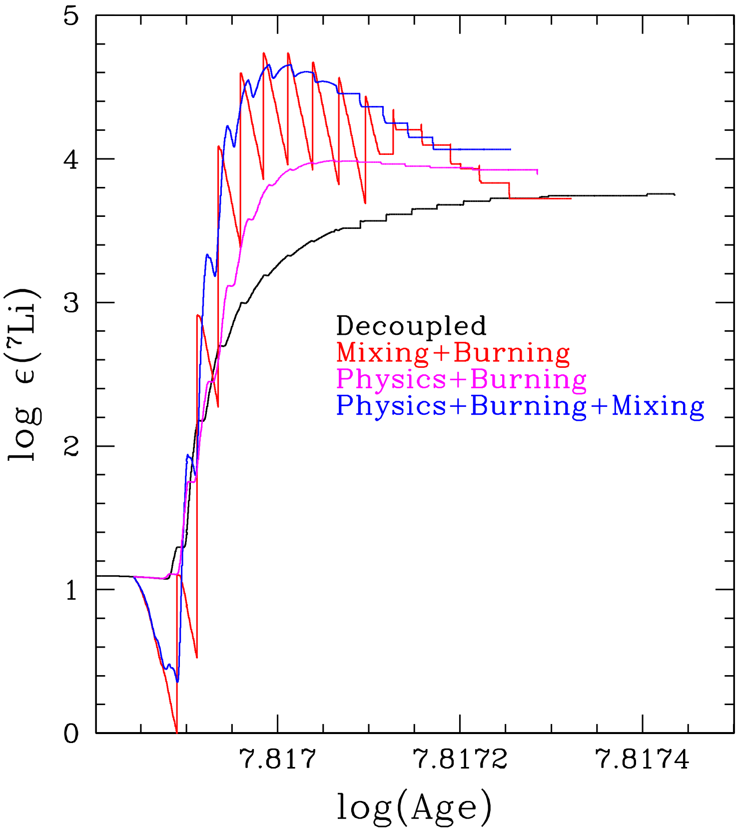

Fig. 4. ^{7}Li surface abundance evolution combining different degrees of coupling in a 6 $M_\odot$ AGB with [Fe/H]=-0.15 (see text for details).

fected by an upward transport (due e.g. to magnetic buoyancy) of fresh synthesized ^{7}Be, fast enough to ensure that it does not undergo destruction by proton and electron captures.

Palmerini et al. (2011) also explored lithium nucleosynthesis in low mass AGB stars. During this phase, a faster circulation rate is at risk of reverting lithium destruction into production. The conclusion of these authors is that Li-poor C stars descend from Li-poor O-stars, while Li-rich C stars descend from Li-rich O-stars. As a matter of fact, the evolution along the AGB is at almost constant lithium: AGB stars owe their Li to the integral of the effects accumulated in previous evolutionary phases. It it worth to stress that these results are still affected by many uncertainties and that other theories have been proposed on the efficiency of magnetic fields to trigger mixing in giant stars. For instance, Charbonnel & Zahn (2007) analyzed the behavior of thermohaline instability in the presence of a magnetic field, concluding that the presence of a magnetic field with B ≈ 10^5 G entirely suppresses thermo-haline mixing[2]. On the other side, Denissenkov et al. (2009) found that magnetic buoyant rising time increases by five orders of magnitude with respect to Busso et al. (2007), with a corresponding increase in the number of magnetic flux rings contributing to the mixing.

[2] Note that these authors did not consider intrinsic magnetic fields instabilities.

5. Hot Bottom Burning

AGB stars with masses larger than 5-6 $M_\odot$ may attain the conditions for hydrogen burning at the base of the convective envelope, where temperature may easily exceeds 30 MK. This phenomenon is commonly know as Hot Bottom Burning (HBB). Among the by-product of HBB, there are large productions of ^{13}C, ^{14}N and ^{23}Na. In the early 1990s, Sackmann, & Boothroyd (1992) showed that AGB stars with masses between $\sim 4_\odot$ and $\sim 8\ M_\odot$ go through a phase in which a significant amount of ^{7}Li can be produced (log $\epsilon(^7\mathrm{Li}) \sim 4$-5) and subsequently transported to the stellar surface (see also Sackmann et al. 1974, Iben 1975, Iben 1977, Boothroyd et al. 1991, Boothroyd & Sackmann 1992). Their results were confirmed by Plez et al. (1993) and Smith et al. (1995), who found Li-rich stars in the Magellanic Clouds. However, those objects are also C-rich (and HBB tends to destroy carbon). Therefore, it became clear that in massive AGBs (and in particular at metallicities lower than solar), two competing mechanisms are at work: TDU (which carry to the surface carbon) and HBB (which tends to destroy it). In such a situation, the synthesis of lithium results even more complex, because TDU can reach hot enough regions to trigger Hot-TDU (which leads to a lithium surface enrichment). On the other hand, HBB itself may lead to a ^{7}Li surface enhancement. However, if strong enough, it can largely destroy it. As a consequence, the final lithium surface model is strongly dependent on the physical recipes adopted to calculate the model. There is a vast literature on this subject (D'Antona & Mazzitelli 1996; Ventura et al. 1999; Ventura & D'Antona 2010; D'Antona et al. 2012, 2019) (see D'Antona contribution, these Proceedings). Firstly, the mixing scheme adopted is extremely important: assuming an instantaneous convective mixing, Iben (1973) could not get high ^{7}Li abundances. On the other side, adopting a time-dependent convective diffusion algorithm coupled to nuclear burning, Sackmann, & Boothroyd (1992) succeeded in producing a large amount of ^{7}Li.

Also the treatment of mass loss is very important, because it hampers the core mass growth (and thus the brightness increase), limiting the increase in the efficiency of the HBB. When the envelope is significantly reduced, the effects of mass loss become particularly important (Mazzitelli et al. 1999), eventually determining the final regime of the calculated model (C-rich or O-rich; Ventura et al. 2000).

Finally, in order to properly compute lithium nucleosynthesis, the different physical processes at work at the base of the envelope of massive AGBs (in particular mixing and burning) have to be coupled. Figure 4 shows as different degrees of coupling may lead to different surface lithium abundances in a 6 $M_\odot$ AGB star with close-to-solar metallicity (Z=10^{-2}, corresponding to [Fe/H]=-0.15). In particular, it is evident that the initial super-lithium rich phase can be obtained only when mixing and burning are coupled.

Although stellar modeling for intermediate-mass AGB stars is able to reasonably reproduce the abundances of ^{7}Li measured in giant stars, the uncertainties affecting the various physical processes involved make it difficult to provide an accurate interpretative picture that reproduces multiple observable at the same time (abundances of ^{7}Li, light elements and heavy elements; luminosity; mass-loss rate). A useful litmus test in this direction is the comparison between lithium and heavy elements synthesized by the s-process (García-Hernández et al. 2007, 2013) (see Garcia-Hernandez contribution, these Proceedings).

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