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Lithium abundances in AGB stars and a new estimate for the ^{7}Be life-time

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Abstract. In most cases RGB and AGB stars with $M \leq 2M_\odot$ destroy Li (which is instead synthesized trough electron-captures on ^{7}Be). This occurs through the combined operation of mixing processes and proton captures, when H-burning operates close to the envelope. Observed Li abundances are however difficult to explain, as they cover a wide spread. Various uncertainties affect model attempts, but so far the largest one concerns the processes of bound and free e-captures on ^{7}Be, hence its life-time, whose known estimates are valid only for solar conditions. RGB and AGB stages have temperatures and densities below the envelope covering a wide range and differing from solar by up to a factor of five for T and up to five orders of magnitudes for ρ, hence extrapolations are unreliable. Recently, we presented an estimate of the ^{7}Be half-life based on a fully quantistic method that goes beyond the Debye–Hückel approximation. Here we discuss its consequences on Li nucleosynthesis in low mass AGB stars.

1. Introduction

The cosmological Lithium abundance remains one of the most important challenges for the Nuclear Astrophysics. Studies of Big Bang nucleosynthesis have not yet alleviated the discrepancy between predictions and observations of ^{7}Li abundances [1] and the stellar contributions to Li evolution in Galaxies have not been completely clarified so far.

^{7}Li, which is the most abundant stable isotope of Li, is produced by stellar H-burning via the p-p chain. In this reaction network the ^{3}He(^{4}He, γ)^{7}Be channel provides the synthesis of ^{7}Be that, undergoing electron captures, decays into ^{7}Li. However, the $^3\mathrm{He} +^4$ He reaction is efficient at temperatures higher than $4{\cdot}10^7$K, while proton captures on ^{7}Be and ^{7}Li take place down to much lower temperatures ($2{\cdot}10^7$K and $2\text{-}3{\cdot}10^6$K, respectively). Therefore, both ^{7}Be and ^{7}Li turn out to be easily burnt into two α-particles. Because of its fragility ^{7}Li is destroyed already in pre-Main Sequence stars, where convection carries it at temperatures of few million Kelvins [2], and observations disagree with theoretical expectations also in further evolutionary stages.

In fact, the spectra of low mass Main Sequence stars reveal that Li is depleted during central hydrogen burning, in solar-like objects as well as in hotter Main Sequence stars of the Galactic disc (producing the so-called Li-dip) [3]. Furthermore, evolved stars, which climb the Red Giant Branch (RGB) and the Asymptotic Giant Branch (AGB), show an even more complicate scenario: the observed Li abundances actually lie in an large spread of values ($-2 \leq \mathrm{A(Li)} \leq 3$)[1]. In principle, massive red giants (M$> 5-6M_{\odot}$) are recognized to be Li-rich objects (A(Li) ≈ 3[4], because of the Hot Bottom Burning phenomenon [5]. Nevertheless, low mass evolved stars (M$\leq 2M_{\odot}$, where envelope temperatures are too low to modify the surface composition) show Li abundances $-2 \leq \mathrm{A(Li)} \leq 2$, pretty difficult to be accounted for by canonical stellar models; the known Li-depletion phenomena, which occur during the previous evolutionary stages, do not seem to justify such a wide distribution of Li abundances.

The unexpected abundances of light elements in low mass stars have been interpreted in terms of mixing episodes of a nature different from pure convection [6], often attributed to rotationally-induced effects [7], atomic diffusion, or the action of stellar magnetic field [8–10].

The energy balance of RGB and AGB stars is mainly ensured by the radiative burning of a thin H-shell below the base of the envelope. Since non-convective mixing processes (often called extra-mixing) should link the convection interface with regions where thermonuclear reactions take place, these phenomena can modify the surface abundances of nuclei involved in H-burning (e.g. C, N, O and Al isotopes) [11]; they are therefore expected to further deplete Li as compared to Main Sequence stages [12].

Despite the uncertainties related to the physical mechanisms driving the phenomenon, parametric models of extra-mixing can reproduce the observational constrains, which are instead inexplicable by standard stellar models [13]. Successful examples are the reproduction of C and N isotopic ratios in low mass RGB stars [14] and of the oxygen isotopic mix in meteorite grains of AGB origins ([15] and reference therein). As already mentioned, extra-mixing episodes might account for the observed trend of Li depletion in RGB stars (with M $\leq 2.3\mathrm{M}_{\odot}$), but a limited number (2%) of giants show Li enhancement at the photosphere and Li observations in most AGB stars do not reveal special trends. In general the observational evidence is believed to be the outcome of the coupling between fast mixing and nucleosynthesis. Indeed, in extra-mixing phenomena Li is destroyed by downward streams of materials in competition with upward transport of ^{7}Be from burning regions; therefore, if the mixing is fast enough ^{7}Be can survive proton captures and undergoes only electron captures in the stellar envelope, so that Li is produced.

Such a complicate scenario is affected by an important uncertainty from nuclear physics: the rate of electron capture on ^{7}Be employed in calculations is often used outside its range of validity. It has been actually estimated by [16] (and further updates e.g.[17]) for the physical conditions of the solar core, while in H-burning regions of RGB and AGB stars, and in those crossed by extra-mixing as well, densities (ρ) are lower than in the solar center (from one to five orders of magnitudes) and temperatures (T) span a range from 70-80 MK down to a few MK.

2. The new estimate for the $^7\mathrm{Be} + \mathrm{e}^-$ rate in stellar plasmas

To correctly estimate ^{7}Be life-time in a plasma it is crucial to determine the contributions of electrons from both bound and continuum states and the total-to-continuum capture ratio. In works devoted to study the $^7\mathrm{Be}(\mathrm{e}^-, \nu_\mathrm{e})^7\mathrm{Li}$ reaction, a Maxwellian distribution of free electron around a Be nucleus is usually assumed (Debye–Hückel approach [18]). This approximation is suitable to describe systems with a large number of electrons and high temperatures, as it is based on the statistical consideration of smooth changes of the potential over a characteristic distance (λ_D), which is larger than the thermal De-Broglie wave-length of the electrons (λ_{DB}).

However, the conditions are at the limits of validity of the Maxwell-Boltzmann gas approximation, already for our Sun. At T= $1.6 \cdot 10^7$K and $\rho = 150\mathrm{g/cm}^3$, $\lambda_D = 0.407$ and $\lambda_{DB} = 0.352$ a.u.. The situation worsens at physical conditions of the H-burning shell in Red Giants, where λ_D might be smaller than λ_{DB}.

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[1] Spectroscopic notation $\mathrm{A(Li)} \equiv \log \epsilon(\mathrm{Li}) = \log \frac{\mathrm{N(Li)}}{\mathrm{N(H)}} + 12$

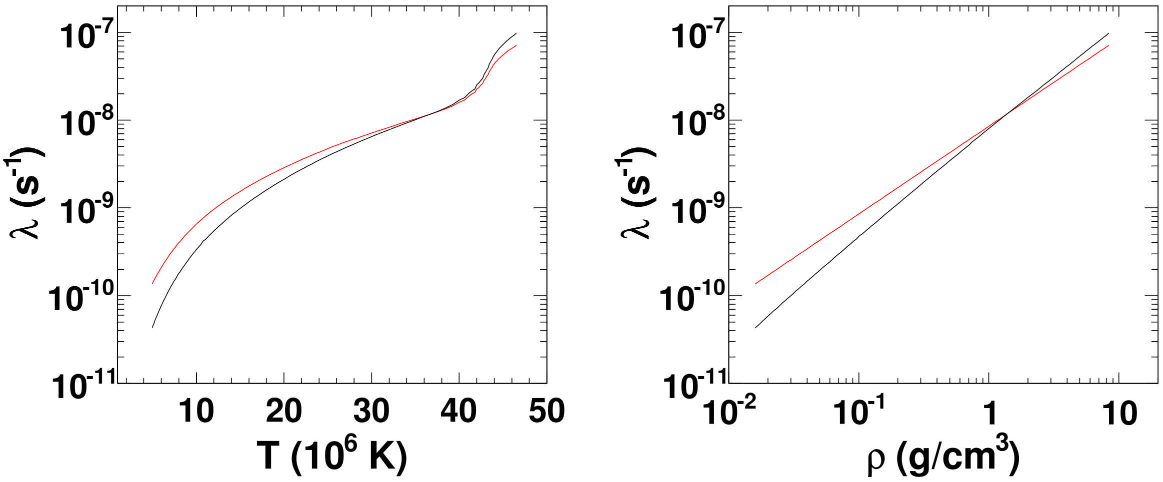

Figure 1. A comparison between the decay rate (λ) of ^{7}Be in the layers between the convective envelope and the H-burning shell during the fourth inter-pulse period of a 2M$_\odot$ AGB star, adopting data by [19] (red line) and the one extrapolated by [17] (black line). λ is plotted as a function of T and ρ (left and right panel, respectively). Notice that although λ is shown as a function of T and ρ separately, it actually depends on both these variables in each layer of the stellar structure.

Simonucci et al. 2013 [19] explore the problem of electron captures on ^{7}Be in stellar environments introducing a new treatment, in which electrons are considered as a Fermi gas and a mean-field adiabatic approximation to the scattering process is used. This is justified by the fact that the Debye–Hückel approach can be derived as a two-step approximation of the more general Thomas-Fermi model, by using the linearized Maxwell-Boltzmann distribution. Furthermore, the two-body (electron-^{7}Be) system is extended by the authors to a many-body interaction scheme by including the Hartree–Focks approximation. In this way electron captures might be computed over a much wider range of T and ρ, with a more precise estimate of the contributions from both bound and free electronic states to the capture. We refer to the paper by [19] for further details about the electron density modeling and the calculation of the ^{7}Be half-life. Here we want to underline that the results of the quoted paper agree well with the previous findings for the Sun (so that no changes to the solar neutrino problem are introduced).

Figure 1 reports a comparison between the ^{7}Be(e$^-$, ν_e)^{7}Li rate computed by [19] and that obtaing using the analytical expression by [17] in the radiative region of a 2M$_\odot$ AGB star of solar composition (as a function of ρ and T). In Fig.1, it is evident that the difference between the two rates of electron capture is larger at lower T and ρ. This portion of the parameter space is very important for Li nucleosynthesis, as only in these conditions does the efficiency of proton captures on ^{7}Be and ^{7}Li decrease sufficiently, so that extra-mixing phenomena can affect the Li abundance in the stellar envelope: this will be a production or a dilution, depending on the mixing rate [12].

3. Lithium abundances in AGB stars

We now analyze the Li nucleosynthesis in AGB stars employing the new estimate for the ^{7}Be + e$^-$ reaction rate. Our reference models for this scope are the ones presented by [12] to discuss the effects of extra-mixing phenomena on Li nucleosynthesis. In the quoted paper, the mixing velocity is related to the mixing rate trough the mass conservation law, thus the extra-mixing

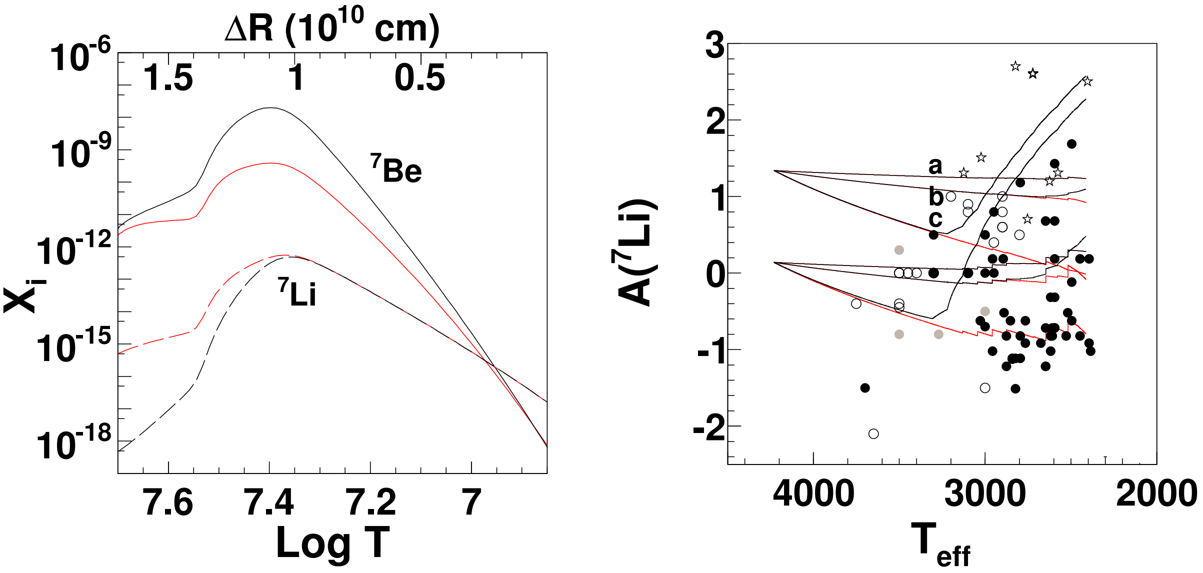

Figure 2. Left panel: comparison between the equilibrium abundances of ^{7}Be and ^{7}Li achieved in the layers above the H-burning shell, adopting the ^{7}Be lifetime by [19] (red line) and that extrapolated by [17] (black line), in the stellar model considered in Fig. 1. On the right side the position $\Delta R = 0$ represents the base of the envelope, while on the left there is the region where the maximum energy is released from H-burning. The matter density is also shown (blue line) and refers to the scale on the right axis. Right panel: curves refer to calculations of Li abundance evolution in the envelope of a 2M$_\odot$ AGB stars of solar compositions: the black line refers to the ^{7}Be life-time from [17] and the red the one to that from [19]. Model curves are characterized by the following extra-mixing parameters: $\Delta T = 0.22$, $\dot{M}_6 = 0.1$(a), 0.3(b), 1(c). The Li abundances observed in O- and C-rich stars on the AGB are also reported. Open, grey and black dots refer to S, SC and C(N) stars, respectively, while open stars show the CJ stars (see [12] and references therein).

models that reach the highest ^{7}Li abundances are those with the largest mixing efficiency $\dot{M}$[2] (black line in the right panel of figure 2). However, another phenomenon contributes to modify the Li abundance in the envelopes of AGB stars: this is the third dredge-up (TDU), which is the deep convective mixing occurring at the end of each recurrent thermal instability, after the enrgy release accompanying the onset of the He burning. In red giant stars, a sort of ^{7}Be-pocket (left panel of figure 2) forms in the H rich zone between the envelope and the H-burning shell. During the TDU such a reservoir is brought by the convection to the surface where it undergoes electron captures enriching the outermost stellar layers in ^{7}Li The ensuing abundance can afterwards be destroyed or further increased by extra-mixing at different rates. The competition between TDU and extra-mixing can determine the large spread of Li abundances observed in low mass AGB stars. The left panel of figure 2 shows the abundances of ^{7}Be and ^{7}Li in the radiative layers below the convective envelope, during the H-burning phase of an AGB star (the model star is the same 2M$_\odot$, solar composition case discussed in [12]). The red lines illustrate the amounts of Li and Be obtained by using the new rate by [19] in calculations, while the black line shows the results with the rate by [17]. The variations shown in the abundances of ^{7}Be and ^{7}Li are entirely due to the different choices adopted for the rate of electron capture on ^{7}Be.

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[2] Extra-mixing mechanisms are generally parameterized and depend on two main parameters; in the approach by [12, 15] these parameters are the mass circulation rate (in units of 10^{-6}M$_\odot$/yr) induced by the transport processes ($\dot{M}_6$) and the maximum depth ΔT they reach.

The same nuclear physics inputs and stellar structure have been adopted to calculate the evolution of surface Li abundances along the whole AGB evolutionary stage (from the early phase up to the last thermal pulse) due to the interplay of extra-mixing and TDU. Results, presented in the right panel of figure 2, are achieved from 2 different initial values of the Li abundance, chosen inside the observed spread left by RGB stages. The black curves show the evolution of Li abundances in the stellar envelope induced by 3 cases of extra-mixing (with parameters $\Delta\mathrm{T} = 0.22$ and $\dot{\mathrm{M}}_6 = 0.1, 0.3, 1$) and using the estimate of ^{7}Be half-life extrapolated by [17]. Results of the same calculation adopting the new Hartree–Focks estimate are instead represented by red curves. The curves showing the Li depletion during the early-AGB are almost insensitive to the rate for e-capture adopted. On the contrary, large changes emerge at the on-set of the thermal pulses (and thus of TDU).

The reason for the above dichotomy can be understood with reference to the left panel of figure 2, where one can see how the ^{7}Be reservoir in the stellar radiative region computed with the new decay rate is smaller than in the previous scenario (at least by a factor of 10). Moreover, the reduction of the ^{7}Be lifetime is strong enough to allow its decay into Li before it is saved to the envelope, even when a fast extra-mixing is at play. As a consequence, Li production becomes impossible in low mass stars with the new $^7\mathrm{Be} + \mathrm{e}^-$ rate, being the destruction of Li in the envelope not compensated. As a consequence, the highest observed Li abundances (typical of CJ stars) cannot be reached.

This finding is now in line with other indications provided by various chemical anomalies of the very peculiar CJ stars, which jointly suggest that these last are not actually normal C-stars affected by deep mixing, but rather the outcome of a more complex evolution, perhaps deriving originally from a binary system. On the other hand, the extra-mixing calculations using the new rate for electron captures on ^{7}Be better reproduce the abundances shown by normal C(N)-stars(solid symbols), whose chemical composition and photometry reveal instead that they do represent a normal family of C-rich AGB stars.

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