PROCEEDINGS OF SCIENCE

PoS(NIC XII)145

Modeling the Li abundances of RGB and AGB stars with a new estimate for the ^{7}Be half-life time

---

Palmerini S.[*]
Departamento de Física Teórica y del Cosmos, Universidad de Granada, Spain
E-mail: `sarapalmerini@ugr.es`

Busso M.[†]
Department of Physics, University of Perugia and INFN sez. di Perugia, Italy
E-mail: `maurizio.busso@fisica.unipg.it`

Simonucci S.

Department of Physics, University of Camerino and INFN sez. di Perugia, Italy

Taioli S.
Interdisciplinary Laboratory for Computational Science, FBK-CMM, Italy
Department of Physics, University of Trento, Italy
Department of Chemistry, University of Bologna, Italy
INFN sez. di Perugia, Italy

Cristallo S.

Osservatorio Astronomico di Teramo, INAF, Italy

Abia C.

Departamento de Física Teórica y del Cosmos, Universidad de Granada, Spain

S. Uttenthaler

Department of Astronomy, University of Vienna, Austria

PROCEEDINGS OF SCIENCE

Stars with $M \leq 2.3 M_\odot$ are considered Li depletion sites during their early and late evolutionary stages. Indeed ^{7}Li, synthesized through electron-captures on ^{7}Be, is burnt into two alpha particles, when the H-shell burns below convective envelopes of Red Giant Branch (RGB) and Asymptotic Giant Branch (AGB) stars. Furthermore, Li abundances observed in the spectra of these stars cover a wide range of values, which is difficult to be explained by stellar models, both Li-rich and Li-poor objects being observed. Difficulties arise in measuring very low Li abundances in O-rich AGBs and the lack of knowledge about the physical causes of extra-mixing, but the main source of uncertainty in investigating Li nucleosynthesis concerns the ^{7}Be life-time, as the available estimations actually are valid only for the Sun [1]. Since in RGB and AGB H-shell burning temperatures and densities might be respectively up to five times higher and five orders of magnitudes lower than in the solar core, using for giants a ^{7}Be life-time, extrapolated from the one valid in solar condition is at least hazardous. We present the consequence on Li nucleosynthesis of a new ^{7}Be life-time estimation computed by a theoretical approach inherited from quantum chemistry. Extra-mixing models integrated with this new datum well reproduce the trends of Li destruction observed in RGBs and are suitable to account for Li observations in AGBs, explaining also the amount of nuclei from C to Al.

XII International Symposium on Nuclei in the Cosmos,
August 5-12, 2012
Cairns, Australia

---

[*] S.P. is grateful to Spanish Grant AYA2011-22460 for the post-doc contract during which this research was carried out.

[†] Speaker.

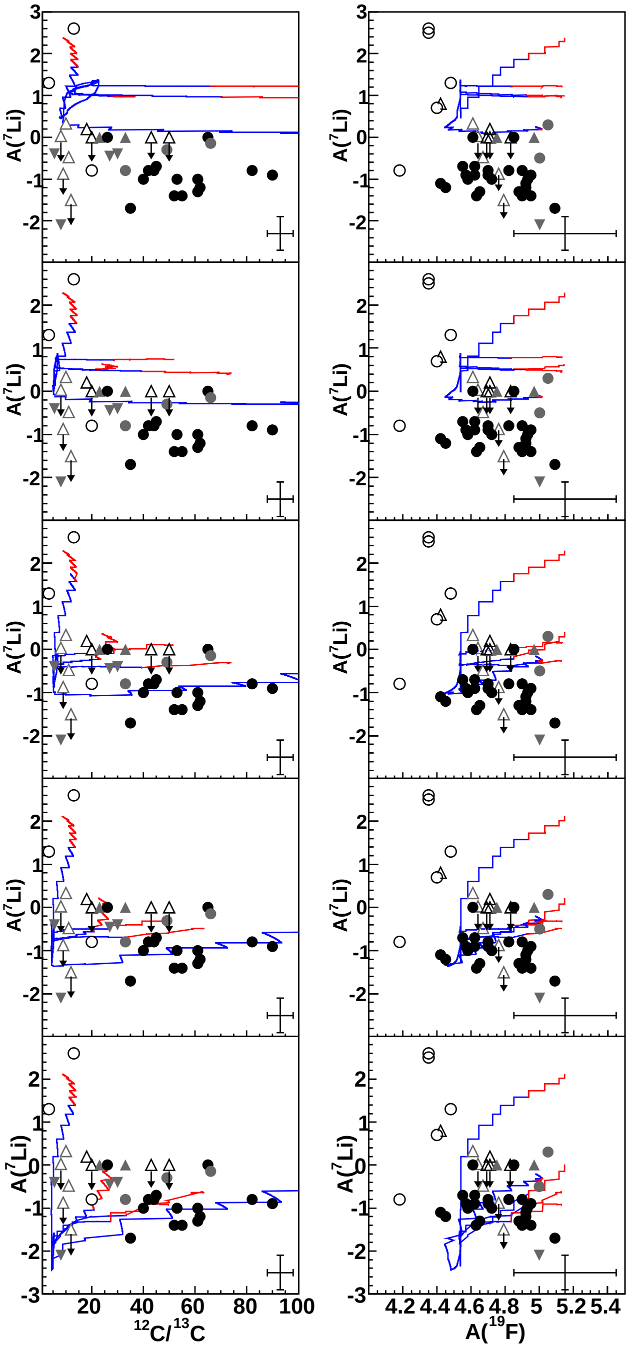

Figure 1: Li abundances in O-rich and C-rich AGB stars as a function of the ^{12}C/^{13}C ratio (left panels) and as a function of F (right panels). Open, grey and black dots refer to J-, SC- and N-type carbon stars, respectively. Grey triangles show abundances in M-, MS- and S-stars. Observations are from [18, 19, 20, 21, 22, 23]. The curves refer to extra-mixing calculations applied to a $2M_\odot$ star of solar metallicity: the blue parts have an O-rich envelope, the red parts a C-rich one. Models with a larger mixing rate reach a higher value of the Li abundance. Different panels refer to extra-mixing calculation starting from different Li abundances as inherited from the previous evolutionary phases (see [11] for more details). Note that efficient extra-mixing sometimes prevents the star to reach the C/O>1 regime.

Lithium nucleosynthesis is one of the most debated topics in nuclear astrophysics. Beyond the well known 'Lithium problem', due to the discrepancy between the predictions and observations of primordial nucleosynthesis, low and intermediate mass stars of population I show a wide spread of ^{7}Li abundances in their spectra, which is difficult to explain by standard stellar models, not including rotation and assumptions for non-convective forms of mixing.

Moreover, large uncertainties in nuclear physics inputs affect our knowledge of Li nucleosynthesis. Indeed ^{7}Li undergoes proton captures at temperatures of a few million K and is synthesized via electron captures on ^{7}Be. Despite the fact that low energy cross sections of ^{7}Li(p,α) and ^{7}Li(p,γ) are relatively well known, because they have been measured through direct and indirect methods by several authors (e.g. [2, 1]), a proper estimation of the ^{7}Be life-time in astrophysical environments different from the solar core is still missing.

In stellar models, the Li abundance is diluted already in the phases of evolution preceding the Main Sequence (MS) because of its fragility [3]. In stars of mass lower than solar, convective envelopes remain large on the MS and Li destruction continues; for higher masses, instead, the external convection shrinks and does not include any longer zones hot enough to affect Li. Contrary to these expectations, observations of the Sun and solar-like stars reveal that they undergo extensive Li-depletion during central hydrogen burning. One of the consequences is that the solar photosphere is about 100 times less Li-rich than meteorites [4]. Li-destruction is known to occur also in hotter MS stars of the Galactic disc (generating the so-called Li-dip) [5].

All the above phenomena, unexpected from canonical models, have been interpreted in terms of mixing episodes different from pure convection [6], often attributed to rotationally-induced effects [7] or magnetic dynamo processes [8]. In more advanced stages, i.e. along the Red Giant Branch (RGB) and the Asymptotic Giant Branch (AGB), similar phenomena must be active [9], perhaps again related to magnetic effects [10]. Such extra-mixing episodes were found to account for the observed trends of Li depletion in RGB stars with $M \leq 2.3 M_{\odot}$. Indeed in more massive objects the H-shell does not advance enough to homogenize the layers below the envelope and mixing is hampered [11]. The consequence is that, in evolved stars, Li is further depleted as compared to MS stages. At odds with the above scenario, a limited number ($\sim 2\%$) of red giants show Li enhancement at the photosphere [7, 12, 13], which could be produced by the coupling between fast mixing and nucleosynthesis [14, 15]. In this hypothesis, the rate at which Li is destroyed by downward diffusion to hot temperatures is over-compensated by upward transport of ^{7}Be from burning regions at a fast enough rate to survive proton captures and to undergo only electron captures in the stellar envelope, reproducing Li.

After the Li-depletion along the first giant branch, in the subsequent AGB phase moderate extra-mixing ($\dot{M} \lesssim 10^{-7} M_{\odot}$/yr might explain the observations of F, C/O, ^{12}C/^{13}C, with a gradual decrease in the Li abundance. If faster mixing occurs, Li destruction might in principle revert into production, if the mixing timescale becomes shorter than the ^{7}Be lifetime. Fast circulation on the AGB also easily brings the ^{12}C/^{13}C ratio to equilibrium and burns F beyond the limits shown by C-rich AGB stars. In Figure 1, the comparisons between some extra-mixing computations and observations of ^{7}Li, ^{12}C/^{13}C and F abundance in a sample of low mass AGB stars are reported. The curves refer to the parametric model presented in [9] and [11] where the mass transport mechanism is characterized by two parameters: the mixing rate $\dot{M}$ and the mixing depth Δ; the latter is indicated by the relation $\Delta \equiv \log T_H - \log T_P$ [1] and kept equal to 0.22 in the cases reported in this paper. $\dot{M}$ values range between 0.01 and $1 \cdot 10^{-6} M_\odot$/yr and, since the mixing velocity is related to the mixing rate through the mass conservation law, the curves that reach the highest ^{7}Li abundances are those dealing with the extra-mixing cases with the largest $\dot{M}$. Moreover, during the AGB phase another phenomenon participates to enrich in Li the stellar envelope: the third dredge-up (TDU), which is the deep convective mixing occurring at the end of each recurrent thermal instability, due to the onset of the He burning. A sort of ^{7}Be-pocket, actually, exists in those stars, in the H rich zone between the envelope and He-shell. During the TDU such a reservoir is brought by the convection to the surface where it undergoes electron capture enriching the outermost stellar layers in ^{7}Li. The stepwise trend of the curves in figure 1 is actually due to the interplay of extra-mixing and TDU episodes.

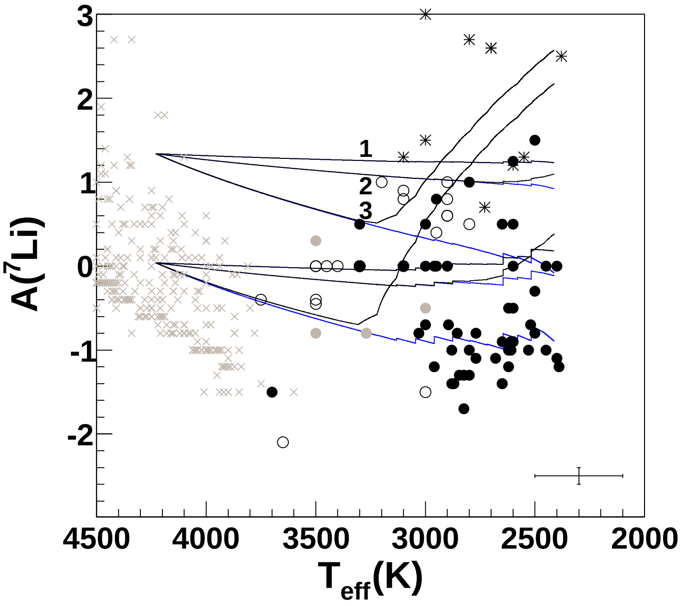

Figure 2: The Li abundances observed in O- and C-rich stars on the AGB. Open, grey and black dots refer to J-, SC- and N-type carbon stars, respectively, asterisks to objects from late K to late M types (see [11] and references therein). The curves refer to our calculation for a $2M_\odot$ star of solar metallicity: the black considering the ^{7}Be life-time from [1] and the blue the one from [16]. Model curves are characterized by the following extra-mixing parameters: Δ=0.22, $\dot{M}$=0.1 (curve labelled 1), 0.3(curve labelled 2), 1(curve labelled 3). Two initial abundances have been considered as starting point for our calculation on the AGB.

The situation is far from being clear, shown by Figure 1 and by [11], as quantitative modeling is hampered by poor knowledge of ^{7}Be decay rate changes in the rapidly varying conditions below the envelopes of red giants. Indeed the above nucleosynthesis calculations, as the ones presented in the literature involving Li, are normally performed adopting extrapolations of the electron capture reaction rate from compilations valid for the Sun [1]. This approach is suspected to be inaccurate because the ambient conditions are very different from solar, while in evolved low-mass stars the

---

[1] Here T_H is the temperature at which the maximum energy is generated by H-burning, and T_P is the temperature of the deepest layer reached by extra-mixing

temperatures of the layers above the H-burning shell span a range from 70-80 down to a few MK. In the same zones, the density is lower than for the solar center by 1 to 5 orders of magnitudes. The explanation of Li abundances in stars has therefore to cope with a poor treatment of the basic nuclear input data, because these two parameters (T and ρ) alter considerably the balance between bound and free electronic states contributing to the capture.

Very recently a reliable method for computing electron captures from first principles has been presented [16]. This technique goes beyond the approximation by Debye-Hückel, employed by Bachall [17] to estimate the electron capture decay rate in stars, as the many-body interaction is explicitly treated; this new approach allows us to compute the ^{7}Be lifetime in physical conditions rather different from the solar case. It turns out that while for the Sun the new estimates are indistinguishable from the previous ones [1], the ^{7}Be lifetime derived by [16] results largely reduced (up to a factor of 10) in the radiative regions of giant stars. The main result of the new calculation is a remarkable increase of the electron density near the nucleus in RGB and AGB conditions, with respect to extrapolations from previous rates valid for the Sun. (See [16] for details).

We employ this new rate for electron capture on ^{7}Be in extra-mixing calculation and we repeat part of the calculation reported in Figure 1 in the light of this novelty in nuclear physics inputs. Figure 2 shows our results: the evolution of Li abundances as a function of decreasing effective surface temperature $T_{\rm eff}$ through the AGB stage (the stellar age increases from left to right). The asterisks represent Li abundances in the peculiar class of CJ-stars, which also show an enrichment in Li. Starting from Li abundances within the range typically observed after core He-burning and adopting the extrapolation to AGB conditions of previous decay rates [1], a Li production roughly fitting the CJ data is found (black curves). The situation is considerably changed assuming the new estimates of the ^{7}Be decay rate. Indeed, now it is not possible to reach the region where CJ stars lie. Although a large enrichment in Li seems not to be achievable, the abundances shown by the spectra of C(N) stars, whose values range in the interval $-1 \leq$A(Li)≤ 1, are easily covered, maybe better than before, by the extra-mixing models (blue curves). On the other hand, the failure in reproducing Li abundances in CJ stars is in line with many other unexplained peculiarities of these very peculiar C-rich giants, including the absence of neutron-capture elements, usually present on the surface of other C-rich stars. We conclude therefore that the unusually high Li abundances of the mysterious CJ stars still represent a challenge, because they cannot be explained by non-convective mixing at commonly-found rates, which instead nicely agree with the observational constraints offered by the non peculiar low mass AGB stars.

References

[1] Adelberger, E.G., Garcîa, A., Robertson, R.G.H., *et al.* 2011, Rev. Mod. Phys. 83, 195

[2] Lamia, L., et al. 2011, A.& A., 541, A158

[3] Sestito, P., DeglÍnnocenti, S., Prada Moroni, P.G., and Randich, S. 2006, A&A 454, 311.

[4] Asplund, M., Grevesse, N.,Sauval, J., and Scott, P. 2009, ARA&A 47, 481.

[5] Boesgaard, A. M., Deliyannis, C. P.,Stephens, A., and Lambert, D. L. 1998, ApJ 492, 727.

[6] Michaud, G. 1986, ApJ 302, 650.

[7] Charbonnel, C., and Lagarde, N. 2010, A&A 522, 10.

[8] Eggenberger, P.,Meynet, G., Maeder, A.,*et al.* 2010, A&A, 519, 116.

[9] Palmerini, S., La Cognata, M., Cristallo, S., and Busso, M. 2011, ApJ, 729, 3.

[10] Busso, M., Wasserburg, G.J., Nollett, K.M., and Calandra, A., 2007, ApJ, 671, 802.

[11] Palmerini, S., Cristallo, S., Busso, M., *et al.* 2011, ApJ 741, 26

[12] Kumar, B. Y., Reddy, B. E., and Lambert, D. L. 2011, ApJ 730, L12.

[13] Uttenthaler, S. and Lebzelter, T. 2010, A&A, 510, 62.

[14] Sackmann, I.-J. and Boothroyd, A. I. 199, ApJ, 510, 217.

[15] Guandalini, R., Palmerini, S., Busso, M., and Uttenthaler, S. 2009, PASA 26, 168.

[16] Simonucci, S., Taioli, S., Palmerini, S., Busso, S. 2012, ApJ, submitted.

[17] Bachall, J. N. 1962, Phys. Rev. 126, 1143.

[18] Denn, G. R., Luck, R. E., & Lambert, D. L. 1991, ApJ, 377, 657

[19] Abia, C., Boffin, H. M. J., Isern, J., & Rebolo, R. 1993, A&A, 272, 455

[20] Jorissen, A., Smith, V. V., & Lambert, D. L. 1992, A&A, 261, 164

[21] Abia, C., Domínguez, I., Gallino R., et al. 2002, ApJ 579 817

[22] Uttenthaler, S., Aringer, B., Lebzelter, T., Käufl, H. U., Siebenmorgen, R., Smette, A. 2008, ApJ, 682, 509

[23] Abia, C., et al. 2010, ApJ, 715, L94