Extra-mixing in red giant stars: challenges for nuclear physics

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Abstract. The existence of extra-mixing phenomena has been often invoked as a possible solution for the Li-abundance puzzle in low-mass red giant stars. In particular, [1] have shown that extra-mixing phenomena induced by stellar magnetic fields can justify the surface Li enrichment as well as its depletion in low mass giants. In the framework of this model, we test here how sensitive is the Li production to the reaction rate for the $^7$Be electron capture, in order to establish whether the presence of intense magnetic fields can alter the Li yield.

1. Introduction
Gratton et al. (2000) [2] set to $\log \epsilon(Li) \leq 0.1$ the upper limit for the Li abundance of low mass and low metallicity stars immediately after the main sequence. The concentration of $^7$Li (which is by far the most abundant lithium isotope) is determined by the interplay between its synthesis by electron capture on $^7$Be and its destruction by proton capture, taking place at relatively low temperatures ($T \leq 2.5 \cdot 10^6 K$). Due to the prevailing destruction effect, $^7$Li is almost totally consumed during the pre-main sequence and main sequence stages. However, red giants with an enhanced Li abundance, sometimes higher than the interstellar medium one [$\log \epsilon(Li) \leq 3.3$], have been observed [3]. This shows that an enrichment should have taken place after the main sequence. Several viable explanations have been proposed, including accretion of Li from outside, such as in the engulfment of a giant planet [4]. Since a thin radiative layer free of entropy barriers is present in the Red Giant Branch (hereafter RGB) stars, between the H-burning shell and the convective envelope, the most common hypothesis has been to assume that some fast extra-mixing should have affected this radiative layer and triggered a Cameron-Fowler mechanism [5]. This a transport of $^7$Be from above the H-burning shell up to the envelope at a rate larger than p-captures along the path. Sackmann & Boothroyd (1999) have shown that it is possible to increase or deplete the Li supply in RGB envelopes by a deep mass circulation mechanism, depending on the mixing depth and velocity. This phenomenon was recognized to be related also to CNO isotopic ratio anomalies in stars along the RGB and the following Asymptotic Giant Branch (AGB) phase.

Several works have investigated causes and mechanisms of extra-mixing (either fast or slow). In particular, processes induced by rotation, with shear instabilities, diffusion and meridional

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1 Throughout the paper, the Li abundance is given on the scale $\log \epsilon(Li) = \log N(Li)/N(H) + 12$. The solar photospheric Li abundance on this scale is $\log \epsilon(Li) = 1.1$. 

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circulation were presented to reproduce the Li enrichment during the initial part of the RGB phase [7], [8]. These possibilities were, to a large extent, frustrated by the discovery that rotation would not yield sufficiently extended extra-mixing processes to account for the observations [9].

More recently, two other extra-mixing models have been proposed as possible sources of deep circulation in stars. The first is the so-called thermohaline diffusion, a double diffusive process of sinking of heavy envelope matter, due to the molecular weight inversion induced by the reaction $^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2\text{p}$ [10]. However, this model provides a slow mixing velocity, while fast a transport is requested to provide for a significant Li enrichment.

The other suggested process is the buoyancy of magnetized H-burning ashes [11], [12]. This second mechanism was shown to be able to lead both to fast and to slow mixing episodes, depending on the buoyant structure geometry [13] and on its heat exchange rate with the surrounding material [14]. More recently Guandalini et al. (2009) [1] presented an analysis of Li abundances (based on the interplay of fast and slow extra-mixing) and proposed a possible evolution of it during the RGB and AGB phases of low mass stars. If the mixing is operated by magnetized structures, the presence of strong fields (up to $10^5$ Gauss) is required in the inner stellar regions, where the Lorentz force could then generate a non-homogeneous charge distribution at microscopic scale. If this were not the case, the magnetic field may affect the nucleosynthesis experienced by mixed materials through changes in the otherwise Maxwellian distribution of the gas velocities, which might in turn modify the effects of electron screening and electron captures.

As an example, in the ppIII-chain network:

$$^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$$  \hspace{1cm} (1)

$$^7\text{Be} + \text{H} \rightarrow ^8\text{B} + \gamma \rightarrow ^4\text{He} + ^4\text{He} + \gamma$$  \hspace{1cm} (2)

$$^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu$$  \hspace{1cm} (3)

$$^7\text{Li} + \text{H} \rightarrow ^4\text{He} + ^4\text{He} + \gamma$$  \hspace{1cm} (4)

reactions (1) and (3) play a key role in determining the $^7\text{Be}$ (and so the $^7\text{Li}$) abundance. In particular, at high temperature ($T > 2 \cdot 10^7$ K) $^7\text{Be}$ is completely ionized and the electron captures take place via free electrons in the plasma. If the electron velocities were not following a Maxwellian distribution, for the presence of a non-kinetic term in their internal energy, introduced by electromagnetic forces, this could significantly modify the efficiency of reaction (3).

In this work, we simulate what could be the resulting Li abundance in red giant stars if the electron capture on $^7\text{Be}$ were inhibited in the material affected by extra-mixing. This is done by repeating the same computation proposed by [1] (for a $2M_\odot$, solar-metallicity star) for different values of this reaction rate, from the nominal accepted value to zero.

2. Magnetic extra-mixing and resulting Li abundances

In RGB stars the hydrogen burning shell surrounds the partly degenerate He-rich core, while in AGB stars there is also a second helium rich shell (below the hydrogen one) surrounding the CO inactive core. Apart from this, the structure of the radiative layer at the base of the convective envelope in a RGB star and in an AGB, during hydrogen shell burning, is almost the same. Fig.1 shows the typical abundances of $^3\text{He}$, $^7\text{Be}$, $^7\text{Li}$ and a few CNO isotopes in the radiative region of a $2M_\odot$, solar-metallicity star on the RGB and on the AGB. In order to increase the envelope abundance of $^7\text{Li}$ the extra-mixing mechanism has to carry rapidly $^7\text{Be}$ from its production zone to cool regions, where p-captures on $^7\text{Li}$ are suppressed because of the low temperatures.

Following the mixing scenario suggested by [1], we consider an initial mixing phase at the RGB luminosity bump$^2$, where only small portions of magnetized material (hereafter called 'bubbles')

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$^2$ The luminosity bump corresponds to the point when the outgoing hydrogen burning shell encounters and erases...
Figure 1. Left panel: Abundances in the radiative region between the H-burning shell and the convective envelope as a function of the temperature (in Kelvin) for a $2 \, M_\odot$ star of solar-metallicity during RGB phase. The dashed black line shows the $^7\text{Be}$ profile obtained using reaction rates from [15]. Instead, the solid black line represents the result obtained by setting to zero the rate of the electron capture on $^7\text{Be}$. (A recent reaction rate measurement of (1) was presented by [16] and it is included in our calculation). The dashed grey vertical line indicates the maximum temperature and hence the deepest layer reached by the extra-mixing. Right panel: Same plot as in the left panel but dealing with the inner structure during the tenth inter-pulse period of the AGB phase.

detach, driven by local magnetic instabilities, from regions near the H shell and travel toward the convective envelope at the Alfvén speed, of a few m/s (case A). Since the motion is very fast, the hypothesis that no burning occurs in this mass circulation is likely. The resulting effect is the mixing of $^7\text{Be}$ (produced near the H shell) into the envelope, where it decays to Li. This first fast mixing phase may be followed by a slow circulation regime [1], where larger structures become buoyant (case B). The mixing velocity is then reduced to values of a few cm/s, due to the gradual heat exchange between the magnetized zones and the surrounding environment [14] and this slow mixing is responsible for Li destruction. This slow mass circulation is assumed to work during the last part of the RGB phase ($\sim 4.7 \, M_\odot \, yr$) and during AGB hydrogen burning periods (the so call ‘inter-pulses’). In both cases, A and B, an equally fast downflow of envelope material guarantees mass conservation.

First, we performed a calculation using the reaction rate from [15] and [16], and the mixing parameters from [1]. Then, we repeated the calculation using the same choices for the stellar model and mixing parameters but under the hypothesis that no electron capture on $^7\text{Be}$ takes place in the radiative zone and inside the magnetic structures.

Fig. 2 shows the temporal evolution of the surface Li abundance of the RGB and AGB stars under study. If electron captures are suppressed, the enrichment of Li in case A is more efficient by a factor of 10 (from $\log \epsilon = 1.3$ to $\log \epsilon = 2.4$). In the same way, the Li depletion obtained in case B is strongly reduced for the RGB star, and can actually be reversed into a production
from $\log \epsilon = -2$ to $\log \epsilon = 2.4$ depending on the mixing rate. Changes in the electron captures induce smaller variations on the AGB. However, also here the rate of Li destruction is reduced and can actually be converted into a (small) production (see Fig.2 right panel).

![Figure 2](image-url)

**Figure 2.** Left panel: Evolution of the envelope Li abundance as a function of the stellar luminosity, during the RGB phase. The dotted lines indicate the Li enrichment due to fast magnetic instabilities (case A). Solid lines show the effects of slower transport phenomena at different mixing rates (case B). These might be induced by the buoyancy of large structures, exchanging heat with the environment. Results presented in Fig.5 by [1], for a mixing rate of $5 \cdot 10^{-7}$ and $10^{-8} M_\odot/yr$ (grey curves), are compared with our results obtained considering no electron captures on $^7\text{Be}$ (black curves). Right panel: Evolution of Li abundance due to slow extra-mixing during the AGB phase, for different mixing rates and different initial abundance of $^7\text{Li}$ in the envelope. As in the left panel, grey curves report results by [1], instead black curves show results obtained considering no electron captures on $^7\text{Be}$.

### 3. Conclusions
Magnetic buoyancy, inducing slow and fast mass circulation, might offer an useful tool to understand Li enrichment and destruction in low mass red giants. However, if the presence of strong magnetic fields (up to $10^5$ Gauss) modified the charge distribution at microscopic scale, this would affect the results of the extra-mixing nucleosynthesis. In particular, we have tested that reduction of electron captures on $^7\text{Be}$ may increase the Li abundance, in some cases by orders of magnitude. Because of its high sensitivity to the temperature and velocity experienced by circulating materials, the stellar Li abundance provides constraints to the extra-mixing model stronger than ones yielded by CNO isotopes. For these reasons, it is crucial to understand whether the magnetic forces can modify the distribution of charges at the microscopic level in the transported materials.

### 4. Acknowledgments
We are indebted to the Italian Ministry of Research for a PRIN grant (n.2006/022731) and to the National Institute of Nuclear Physics (Section of Perugia, ERNA experiment) for providing support and computing facilities.
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