LITHIUM ABUNDANCE DISPERSION IN METAL-POOR STARS

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Abstract. The formation and evolution of light elements in the Universe act as important cosmological constraints. The oldest stars of the Galaxy have long been assumed to display in their outer layers the primordial lithium abundance, although all studies of stellar physics proved that this abundance must have decreased with time. The primordial Li abundance deduced from the observations of the Cosmological Background is indeed larger than the maximum one observed in these stars. Recent observations gave evidence of a large Li abundance dispersion in very metal poor stars.

We address the general question of the lithium abundance dispersion obtained from observations of metal-poor stars, and more specifically of Carbon Enhanced Metal Poor stars rich in s-process elements (CEMP-s), and how the interplay of atomic diffusion and accretion of matter modifies the element abundances in these metal-poor stars. In particular, we focus on the hydrodynamic processes that could take place after accretion. We consider initial metallicities from [Fe/H]=−2.31 dex down to [Fe/H]=−5.45 dex.

We show that the observations of lithium dispersion, associated with carbon enrichment, are well accounted for in terms of accretion onto the metal-poor stars, with accreted masses smaller than a few Jupiter masses, when using a lithium initial abundance in accordance with the primordial lithium abundance obtained from latest Big Bang Nucleosynthesis results.

Keywords: stars: Population II, stars: abundances, accretion, diffusion, instabilities

1 Introduction

The observations of light elements in the Universe act as important cosmological constraints. For this purpose, their evolution over time must be precisely reconstructed through modelling. Among these elements, lithium plays a special role as it was the subject of numerous observations, in particular in the oldest stars of the Galaxy. For a long time the lithium surface abundances obtained for these old stars was assumed by some to be the primordial lithium abundance. The main argument for this assumption was the absence of dispersion on lithium abundances in the so-called "lithium plateau" stars (Spite & Spite 1982), which seemed incompatible with stellar lithium depletion. More recently, the evidence of a large lithium dispersion in the extremely metal-poor stars modified the landscape (Bonifacio et al. 2007; Cayrel et al. 2008; Sbordone et al. 2010). On the other hand, the primordial lithium abundance determined through Cosmological Microwave Background observations is 3 to 4 times larger than the present lithium surface abundances obtained in metal poor stars of the lithium plateau (Cyburt et al. 2016; Coc & Vangioni 2017) and led to the "lithium problem". However this gap between the primordial lithium and the lithium surface abundances of these old stars of the lithium plateau is expected if considering transport processes inside the stars and is qualitatively consistent with stellar modelling, as the surface lithium abundances decrease over time as shown since several decades (e.g. Michaud et al. 1984; Vauclair 1988; Proffitt & Michaud 1991; Vauclair & Charbonnel 1995; Richard et al. 2005; Vick et al. 2013). Recently, Deal & Martins (2021) showed that taking into account atomic diffusion, rotation-induced mixing, and penetrative convection in stellar models contributes to reconcile Big Bang Nucleosynthesis (hereafter BBN) primordial lithium with that of the plateau.

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All these observations, from the lithium plateau to the extremely metal-poor stars, have to be reconciled, by deep studying of the possible lithium abundance evolution inside these stars. As a first step, we focused our study on the case of Carbon Enhanced Metal Poor stars rich in s-process elements (here after CEMP-s), for which many data are available. These stars are characterised by [Fe/H]<2 dex and [C/Fe]$>0.7-1$ dex (Beers & Christlieb 2005; Aoki et al. 2007). The abundance variations observed in these stars are generally explained in terms of accretion of the wind of stellar companions, especially Asymptotic Giant Branch stars (McClure & Woodsworth 1990; Stancliffe et al. 2007; Jorissen et al. 2016), taking into account the stellar structure and the thermohaline convection that take place after accretion. Thermohaline convection occurs when the thermal gradient is stable and the mean molecular weight gradient unstable. When a blob of matter falls towards the centre of the star, the heat gets in more quickly than the particles get out, and the blob keeps on sinking. This effect generates a mixing of chemicals in that region. Such an instability may occur in stars whenever heavy elements accumulation occurs on top of lighter ones. This is the case, for example, during the main-sequence phase after episodes of accretion (Vauclair 2004; Stancliffe et al. 2007; Théado et al. 2010; Garaud 2011; Deal et al. 2013, 2015; Wachlin et al. 2017, and reference therein).

Previous studies of such accretion scenarios from an AGB companion onto a main-sequence star showed their potentiality in explaining the formation of CEMP-s stars. They reproduce relatively well the surface abundances of these stars from the main sequence up to the red giant phase (Stancliffe et al. 2007; Stancliffe & Glebbeek 2008; Stancliffe 2009; Matrozis & Stancliffe 2016, 2017). However, the question of the lithium dispersion was not addressed, neither the effect of metallicity. These simulations were only done for $[\mathrm{Fe/H}]_{\mathrm{ini}} = -2.31$ dex. We extended our own study down to $[\mathrm{Fe/H}]_{\mathrm{ini}} = -5.45$ dex. We also considered a range of smaller accreted masses, which was not explored before, and we used more precise and up-to-date prescriptions for atomic diffusion and thermohaline convection. We focused our study on how such accretion processes modify the surface Li abundances. We took into account the stellar parameters of the primary star, the parameters of the AGB companion, the wind composition, the atomic diffusion and hydrodynamic processes that have important consequences on the final results. The full study is available in Deal et al. (2021).

2 Method

In order to explain the lithium dispersion also seen in CEMP-s star, we computed stellar models with the Montréal/Montpellier stellar evolution code (Turcotte et al. 1998; Richard et al. 2001), considering initial [Fe/H] between -2.31 and -5.45 dex and masses of 0.7, 0.75 and 0.78 $\mathrm{M}_\odot$. Atomic diffusion was taken into account, including radiative accelerations using the formalism of Burgers (1969). We included a parametrised turbulent diffusion coefficient calibrated to reproduce the Li plateau as described in Richard et al. (2005). We included the effect of thermohaline convection from recent 3D simulations (Brown et al. 2013). We considered accreted masses between 0.0038 and 4 $M_{\jupiter}$ from AGB winds of 1, 2 and 3 $M_\odot$ companions (leading to accretion age of 5.83 Gyr, 0.748 Gyr and 0.27 Gyr, respectively). The chemical compositions and accretion ages of the AGB winds are taken from Stancliffe & Glebbeek (2008) and Campbell & Lattanzio (2008).

3 Lithium abundances in CEMP-s stars: comparison between models and observations

The lithium dispersion in CEMP-s is shown in Fig. 1 (grey squares) and goes from the plateau value (A(Li)$=2.2\pm 0.2$ dex) down to at least 1 dex. One must notice that about half of the observed lithium abundances are in fact upper limits, so that the real lithium abundance may still be smaller. In addition we have plotted the lithium surface abundance predicted by models of CEMP-s stars, for AGB companions of 2 and 3 $\mathrm{M}_\odot$ (see Deal et al. 2021 for the 1 $\mathrm{M}_\odot$ case). We see that our models correctly reproduce the lithium dispersion for accreted masses between 0.4 and 4 $M_{\jupiter}$ (see middle and right panels of Fig. 1), both in terms of T_{eff} and surface [Fe/H]. We also show that the mass of the AGB companion, hence the chemical composition of the wind, has a strong impact on the accreted mass needed to induce a lithium depletion. We also show that the lithium dispersion occurs only when the proto-CEMP-s becomes a CEMP-s (i.e. [C/Fe]>0.7), as shown on the left panels of Fig. 1. This means that the scenarios that explain the lithium dispersion in CEMP-s stars can be different from the one(s) explaining C-normal metal poor stars.

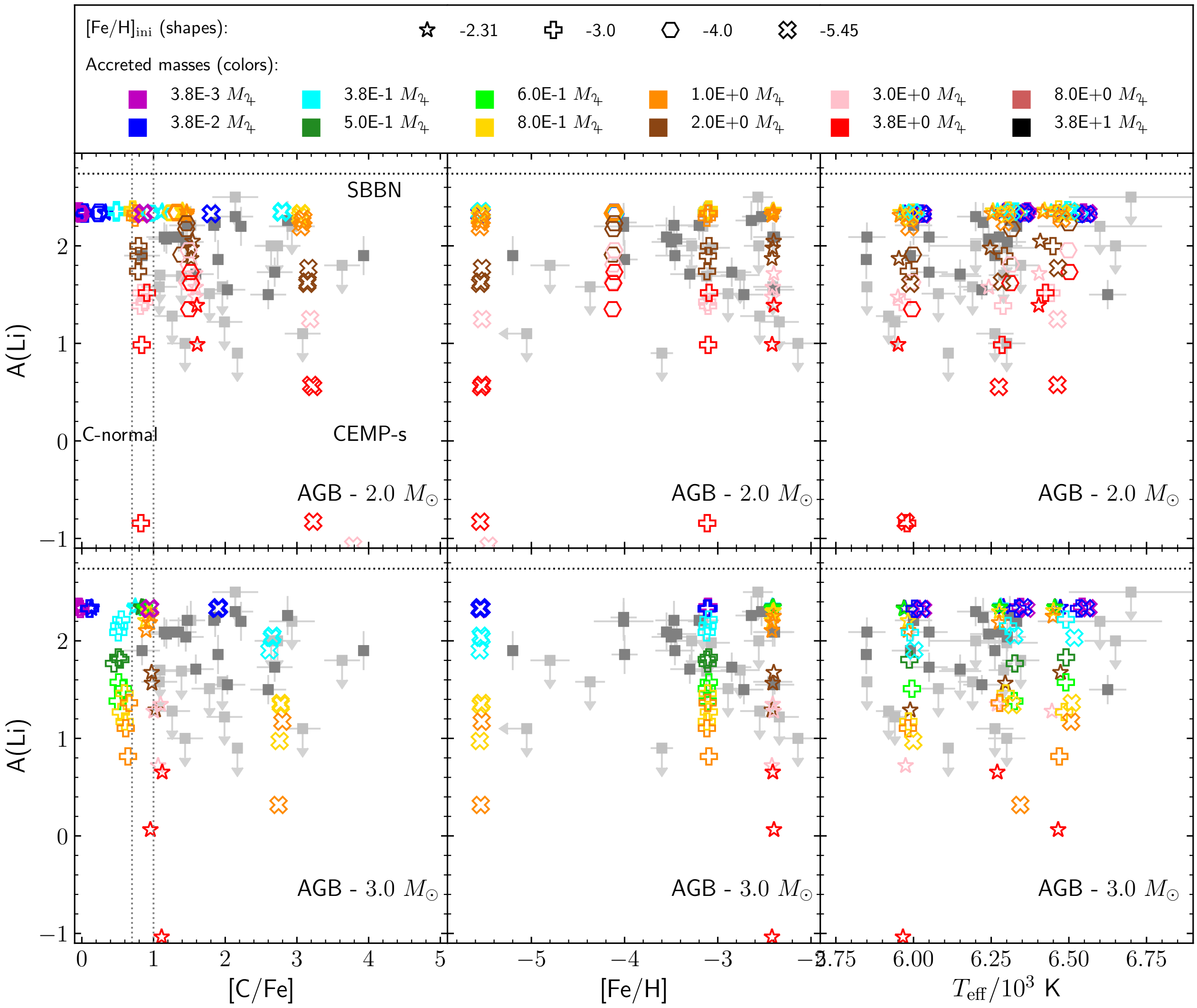

Fig. 1. Lithium surface abundances obtained in our models at the age of 12.5 Gyr. The various metallicities of the models are represented by the shapes of the open symbols and the accreted masses by their various colours. Each model includes an accretion episode of AGB wind at a specific age depending on the AGB mass (270 and 748 Myr for AGB stars of 3 and 2 $M_{\odot}$, respectively). The left column presents the Li results according to [C/Fe]. The vertical dotted lines correspond to [C/Fe]=0.7 and 1.0. The horizontal dotted lines are the BBN lithium abundance that has been used as the initial abundance in our computations. In the middle column, the lithium surface abundances are displayed as a function of [Fe/H] obtained in the same models at the same age. In the right column, the lithium surface abundances are displayed as a function of $T_{\rm eff}$. The grey squares represent the observations, light-grey squares are upper limits. The observations are from the SAGA data base (`http://sagadatabase.jp/`: Suda et al. 2008, 2011, 2017; Yamada et al. 2013, and Matsuno et al. 2017).

4 Conclusions

We show that the observations of the lithium abundance dispersion in CEMP-s stars are well accounted for in terms of accretion of the winds of AGB companions. The needed accreted masses are smaller than those considered in previous studies. The initial lithium abundance value that we used in the models is in accordance with the primordial one, determined by cosmological observations. This also shows that the lithium dispersion observed in metal poor stars is linked to stellar interior processes, and that the so-called lithium problem is no more a problem when realistic treatments of the transport processes of chemical elements are taken into account in stellar models.

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