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Explaining the lithium meltdown in the dwarf stars using the red giant branch stars

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Abstract. The lithium abundance, A(Li), in oldest stars is a key element in our understanding of the Big Bang nucleosynthesis. A(Li) remains constant in dwarf stars down to [Fe/H]∼–2.8 dex and, at lower metallicity, drops by 0.3 dex. The origin of this lithium meltdown is still unclear: this drop could be real (challenging the current models for the primordial nucleosynthesis) or due to (still unknown) settling/diffusion mechanisms. Lower red giant branch stars are insensitive to the diffusion effects occurring in dwarf stars and they allow to investigate the real behaviour of A(Li) at low metallicity. We discuss the A(Li) distribution measured in a large sample of lower red giant branch stars.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II

1. Introduction

The Universe formed with a primordial chemical composition made essentially of H and He, and only traces of Li. The production of these elements occurred in the first minutes after the Big Bang, some tens of million years before that the first stars began to shine. The last decade has seen a significant improvement in our knowledge of the cosmological constants and parameters, thanks to the high precision measures of the cosmic microwave background provided by WMAP and Planck satellites. Measurements of deuterium and helium abundances nicely agree with the most recent cosmological predictions. Only regarding ^{7}Li, the measured abundances, A(Li), heavily disagree with the cosmological calculations, posing hard questions on the reliability of both the observational approach and the Big Bang nucleosynthesis standard model (see e.g. Spite et al. 2012).

Up to now, all the information about the initial lithium abundance of the Universe at our disposal comes from old, dwarf stars. In fact, the old stars should be the natural environment where to measure A(Li) because the signature of the Big Bang nucleosynthesis is imprinted in the surface chemical composition of the first stars born in the Universe. All the Population II, dwarf stars in the metallicity range between [Fe/H]∼–2.8 and –1.0 dex share the same lithium content (A(Li)∼2.2-2.3 dex), the so-called Spite Plateau (Spite & Spite 1982). This constant abundance of the Spite Plateau has been interpreted as the signature of the lithium produced after the Big Bang. However, this interpretation has been contradicted by the results of the WMAP and Planck satellites that provide values of the primordial lithium abundance of ~2.7 dex (Coc et al. 2013), a value higher (of a factor of three) than that of the Spite Plateau. Un to now, this lithium discrepancy remains an unsolved riddle.

An additional piece of the puzzle is the discovery of the so-called lithium meltdown (Sbordone et al. 2010). Among the dwarf stars, A(Li) remains constant down to [Fe/H]~-2.8 dex, while for lower metallicities this abundance drops below the level set by the Spite Plateau by 0.3 dex per dex in [Fe/H] and with a larger number of stars with low A(Li) (see e.g. Fig. 2 in Aguado et al. 2019). The origin of this feature is still unclear: it could reflect a real under-abundance of lithium (not predicted by the Big Bang nucleosynthesis) or it could be due to some settling/diffusion mechanisms, able to hide part of the lithium below the observable photosphere of the most metal-poor stars.

The discovery of the lithium meltdown (and the lack of a theoretical explanation) makes hard to constrain the initial lithium abundance in these stars. The understanding of this feature is also crucial to well constrain the mechanisms that can modify the surface lithium abundance in dwarf stars and hence reconcile the Spite Plateau with the cosmological calculations.

2. Lithium abundance in lower red giant branch stars

Mucciarelli et al. (2012) proposed an alternative route to establish the initial lithium content in Population II stars, namely the use of the surface lithium abundance in the so-called lower red giant branch (LRGB) stars. These stars evolve between the completion of the first dredge-up (where Li-free material is mixed to the surface by convection, decreasing the surface abundance) and the luminosity level of the RGB bump (where an additional mixing episode destroys the surviving lithium). These giants are characterised by a constant lithium abundance, drawing a plateau that mirrors the Spite Plateau but at a lower lithium abundance (A(Li)~0.9-1.0 dex). The amount of lithium depletion due to the first dredge-up is robustly predicted by the canonical stellar evolution theory, allowing to easily determine the initial lithium abundance of these stars. Also, the LRGB stars do not suffer of the uncertainties in the efficiency of the settling/diffusion process that heavily affect dwarf stars. The use of LRGB stars remove the large modeling uncertainties that are the main stumbling block when dwarf stars are used to derive the primordial lithium abundance. In other words, the LRGB stars preserve memory of their initial lithium abundance, revealing what the dwarf stars hide. This innovative tool has been already successfully used to derive the initial lithium content in Galactic Halo (Mucciarelli et al. 2012) and globular cluster stars (Mucciarelli et al. 2011) and in the extra-galactic globular cluster M54 in the Sagittarius dwarf galaxy (Mucciarelli et al. 2014). This latter case represents the first determination of the initial lithium abundance obtained so far for old stars outside of our Galaxy.

Because any modification of the surface lithium abundance driven by settling processes among the dwarf stars is totally erased in LRGB stars, the LRGB stars are a powerful tool to unveil the true lithium abundance of stars, isolating the contribution of atmospheric processes (that affect the dwarf stars) from the original lithium abundance.

3. The new sample of LRGB stars

In principle, the LRGB stars with [Fe/H]<–2.8 dex should mirror the same abundance behaviour observed in dwarf stars. If the observed lithium depletion in such extremely metal-poor dwarf stars is real, we should observe the same drop among the metal-poor LRGB stars. On the other hand, if the metal-poor LRGB stars will display the same lithium abundance of the LRGB stars with higher metallicity, this will demonstrate that the lithium meltdown does not reflect a real (lower) original abundance but it is likely due to settling processes. In this latter case, the metal-poor LRGB stars will become the best tool to measure the initial lithium abundance in this metallicity regime, because

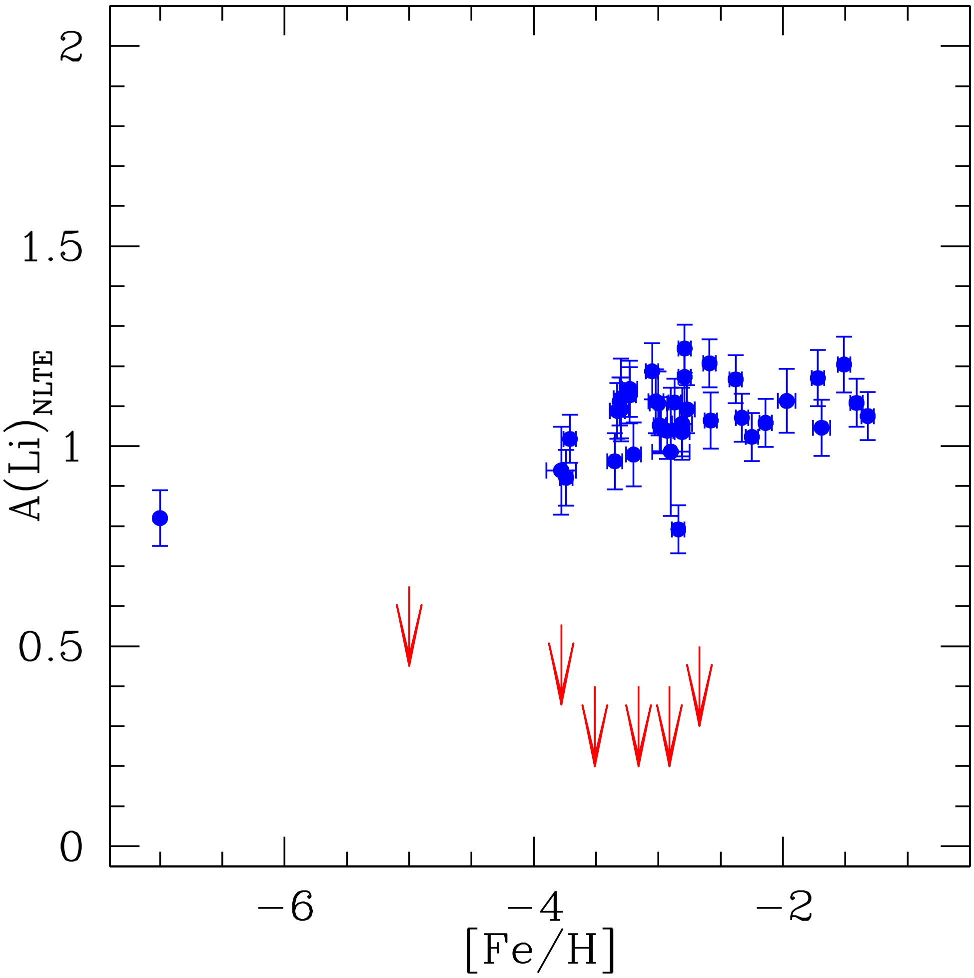

Fig. 1. Behavior of the surface Li abundance as a function of the iron content [Fe/H] for the LRGB stars of our sample: blue circles are the true measures, while red arrows indicate upper limits.

they are not affected by additional (and uncertain) atmospheric processes.

The previous sample discussed by Mucciarelli et al. (2012) has been enlarged in order to better investigate the very metal-poor stars ([Fe/H]<-3.0 dex). The new sample includes a total of 44 LRGB stars observed with the high-resolution spectrographs (R>40,000) UVES at the ESO-VLT, MIKE at the Magellan Telescope and ELODIE at the Observatoire de Haute-Provence. The sample includes also 10 Carbon-enhanced metal-poor (CEMP) stars, two of them classified as CEMP-s.

Effective temperatures have been homogeneously determined for all the stars adopting the infrared-flux method calibration provided by González Hernández & Bonifacio (2009). Surface gravities have been derived from the photometry and adopting the parallaxes from GAIA Data Release 2 (Gaia Collaboration et al. 2018). Lithium abundances have been determined from the Li line at 6707.7 Å and corrected for the departures from LTE using the corrections provided by Lind et al. (2008).

Fig.1 shows the behavior of A(Li) as a function of [Fe/H] for the sample of 44 LRGB stars (blue circles are the true measures, while red arrows indicate upper limits). When we consider only the true measures, the LRGB stars exhibit a constant A(Li) over a large range of metallicity, with a star-to-star scatter compatible with the uncertainties. The most metal-poor stars (with [Fe/H]<–3.5 dex) seem to have a slightly lower A(Li), however this mild correlation between A(Li) and [Fe/H] is smaller than that observed among dwarf stars. Also, six LRGB stars have A(Li) significantly lower than those measured in the other LRGB stars. The two CEMP-s stars are in this sub-sample and their lack of Li is compatible with their origin from binary systems. The analysis of this sample of LRGB stars points out that the A(Li) distributions in dwarf and LRGB stars are different, suggesting that the large dispersion observed in very metal-poor dwarf stars could be due to settling processes.

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