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Signatures of stellar depletion on the Spite plateau

Jorge Meléndez

Departamento de Astronomia do Instituto de Astronomia, Geofisica e Ciências Atmosféricas, Universidade de São Paulo, Rua do Matão 1226, São Paulo, Brazil
e-mail: `jorge.melendez@iag.usp.br`

Abstract. The predicted primordial lithium abundance is about three times higher than the Li abundance inferred from spectroscopic observations of metal-poor stars on the Spite plateau. This cosmological problem could be explained either by exciting new physics or by stellar depletion during the pre-main sequence and/or the main sequence. We discuss the Li abundance pattern in different stellar populations, showing that the Spite plateau is 'universal', meaning that the Li problem is present in distinct Galactic and extra-galactic populations. We discuss high precision and homogeneous studies of large sample of stars, covering different stellar masses and metallicities. Clear atomic diffusion signatures are observed in globular clusters, indicating important stellar Li depletion. Among main sequence field stars, there is a significant decrease of lithium abundances for both lower effective temperatures and lower stellar masses, suggesting that stellar depletion is the cause of the cosmological lithium problem.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: abundances – Cosmology: observations

1. Introduction

The cosmological lithium problem is the discrepancy between the primordial Li abundance A(Li) ~2.7 predicted by Standard Big Bang Nucleosynthesis (SBBN) models (e.g., Fields et al. 2019; Pitrou et al. 2018; Cyburt et al. 2016) and the observed lithium abundance A(Li) ~ 2.2±0.2 in relatively unevolved warm metal-poor stars, the "Spite plateau" stars (e.g., Aguado et al. 2019; Matsuno et al. 2017; Reggiani et al. 2017; Spite et al. 2015; Schaeuble & King 2012; Sbordone et al. 2010; Meléndez et al. 2010; Aoki et al. 2009; Shi et al. 2007; Bonifacio et al. 2007; Asplund et al. 2006; Boesgaard et al. 2005; Charbonnel & Primas 2005; Meléndez & Ramírez 2004; Ryan et al. 2001, 1999; Bonifacio & Molaro 1997; Spite et al. 1996; Ryan et al. 1996; Molaro et al. 1995; Thorburn 1994; Hobbs & Thorburn 1991; Rebolo et al. 1988; Boesgaard 1985; Spite et al. 1984; Spite & Spite 1982). Albeit most Spite plateau stars have A(Li) ~ 2.2, there seems to be a decrease towards lower metallicities (e.g., Meléndez et al. 2010; Asplund et al. 2006; Ryan et al. 2001), reaching A(Li) ~ 2.0 approximately below [Fe/H] < -3.5 (e.g., Aguado et al. 2019; Matsuno et al. 2017; Sbordone et al. 2010).

The large conflict of about a factor of three between SBBN and observations in halo stars, could be alleviated through the use of exciting new physics (e.g., Clara & Martins 2020; Kang et al. 2019; Kusakabe et al. 2017; Mosquera

& Civitarese 2017) or internal stellar depletion (e.g., Gruyters et al. 2016; Fu et al. 2015; Meléndez et al. 2010; Korn et al. 2006; Richard et al. 2005; Salaris & Weiss 2001; Pinsonneault et al. 1992; Deliyannis & Demarque 1991; Deliyannis et al. 1990).

A possible second cosmological lithium problem has been discussed, due to the apparent high abundances of the Li-6 isotope in metal-poor stars (e.g., Asplund et al. 2006; Cayrel et al. 1999; Smith et al. 1998). However, realistic 3D model atmospheres and non-LTE line formation reveal no detections of Li-6 in metal-poor stars (Lind et al. 2013; Cayrel et al. 2007). Recent ESPRESSO/VLT observations analysed in 3D+NLTE presented at the 2019 Lithium in the Universe conference [1] by E. Wang, also find no detectable Li-6 in metal-poor stars.

2. The Spite plateau in different stellar populations

Besides the many works on lithium abundances in field halo stars (see references cited above), there are diverse measurements in globular cluster turnoff stars (Gruyters et al. 2016, 2013; Monaco et al. 2012; Lind et al. 2009; Korn et al. 2006; Pasquini et al. 2005; Bonifacio et al. 2002; Thévenin et al. 2001; Boesgaard et al. 1998), which show a similar Li abundance to Spite plateau field stars, but with some variations due to pollution of the pristine globular cluster gas (Shen et al. 2010; Pasquini et al. 2005) and atomic diffusion effects (Gruyters et al. 2016, 2013; Lind et al. 2009; Korn et al. 2006).

In relation to lithium in stars from other galaxies, Nissen & Schuster (2012) show that high-α stars, which are formed in situ in the Galactic halo, have similar Li abundances to low-α stars, which are accreted from dwarf galaxies. Li in the globular cluster M54 from the Sagittarius Dwarf Spheroidal galaxy, has been measured in red giants (Mucciarelli et al. 2014), and after taking into account the dilution due to the dredge-up, it has been inferred to be compatible with the Li content of Spite plateau stars.

Regarding the population of Galactic thick disk metal-poor stars, different studies indicate that their Li abundances are close to the abundances of Spite plateau halo stars (e.g., Bensby & Lind 2018; Fu et al. 2018; Prantzos et al. 2017; Guiglion et al. 2016; Delgado Mena et al. 2015; Ramírez et al. 2012; Molaro et al. 1997).

The Galactic bulge metal-poor main-sequence population has been studied for lithium through microlensing events, and show Li abundances compatible with the Spite plateau (Bensby et al. 2020, 2010).

Thus, we can conclude that the Spite plateau (Spite & Spite 1982) is universal and that the cosmological Li problem exists for diverse Galactic and extra-galactic populations.

3. Signatures of stellar depletion

A trend between Li abundance and effective temperature within the Spite plateau has been observed (e.g., Meléndez et al. 2010; Sbordone et al. 2010; Ryan et al. 2001, 1999; Bonifacio & Molaro 1997), suggesting internal lithium depletion. Indeed, several theoretical works show that different amounts of Li can be depleted inside metal-poor stars, depending on the assumptions made in the modeling (Fu et al. 2015; Richard et al. 2005; Salaris & Weiss 2001; Pinsonneault et al. 1992; Deliyannis & Demarque 1991; Deliyannis et al. 1990). In particular, notice that in some models Li is mostly depleted during the pre-main sequence (Fu et al. 2015), while in others is mainly during the main sequence (Richard et al. 2005).

Correlations between Li abundance and [Fe/H] have also been noticed (e.g., Matsuno et al. 2017; Meléndez et al. 2010; Aoki et al. 2009; Asplund et al. 2006; Ryan et al. 2001), suggesting that Li depletion depends on metallicity, as predicted by some stellar models (Deliyannis & Demarque 1991).

Meléndez et al. (2010) analysed correlations between lithium and mass in field stars, showing qualitative agreement with the Richard et al. (2005) atomic diffusion models. The recent work by Reggiani et al.

[1] `https://lithiumintheuniverse.wixsite.com/lithium2019`

2021 (in preparation), revisited the analysis of Meléndez et al. (2010), significantly increasing the sample of metal-poor stars analysed homogeneously at high precision. The effective temperatures were determined using the InfraRed Flux Method (IRFM) $T_{\rm eff}$ scale by Casagrande et al. (2010), surface gravities using GAIA DR2 parallaxes (Gaia Collaboration et al. 2018), and metallicities are averaged values from the literature. The reddening was estimated from several maps, as described in Meléndez et al. (2006). Only high precision observations were considered, mostly from UVES/VLT or HIRES/Keck observations, leading to precise equivalent width measurements. Reggiani et al. 2021 (in preparation) found significant correlations both with effective temperature and [Fe/H], suggesting metallicity-dependent lithium depletion. Also, there is a clear correlation between Li and stellar mass, strengthening the suggestion of Li depletion in metal-poor stars.

Clear signatures of atomic diffusion are also present in homogeneous analyses of globular clusters, as stars in different evolutionary stages follow the model predictions, not only for lithium, but for other chemical elements as well (Gruyters et al. 2016, 2013; Lind et al. 2009; Korn et al. 2006).

Stellar depletion is not only a plausible solution for the cosmological lithium problem, but is also important to explain the solar lithium problem and the depletion of lithium with age in solar twins (Monroe et al. 2013; Carlos et al. 2016, 2019). The Li abundance in the Sun's photosphere is about a factor of 160 lower than in meteorites (e.g., Asplund et al. 2009). As the temperature at the bottom of the convection zone is not high enough to burn lithium, extra-mixing mechanisms (e.g., Thévenin et al. 2017; Zhang & Li 2012; Denissenkov 2010; Xiong & Deng 2009; Do Nascimento et al. 2009; Charbonnel & Talon 2005) have to be invoked in order to solve the solar Li problem. Thus, further work on stellar models are required to explain the lithium abundances of both metal-poor stars and solar-metallicity stars.

4. Conclusions

Metal-poor stars in the field and in globular clusters, show different signatures of stellar depletion, in agreement with some stellar evolution models. Thus, internal Li depletion seems a plausible solution to explain the cosmological lithium problem.

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