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Lithium depletion in solar analogs

Age, mass, and planet effects

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Abstract. The goal of this work is to evaluate the correlation between Li abundance, age, and mass. The high quality spectra (R ≃ 115 000; 270 ≤ SNR ≤ 1000) used were observed with ESO/HARPS. The stellar atmospheric parameters were found by imposing the excitation and ionization equilibria of iron lines, and Li abundances were determined via spectral synthesis of the 6707.8 Å ^{7}Li line. Our joint analysis of 151 solar-type stars confirms the strong Li abundance-age correlation reported by other works. Mass and convective envelope size also seem to be connected with Li abundance but with lower significance. We have found a link between the presence of planets and low Li abundances in a sample of 192 stars with a high significance.

Resumo. O principal objetivo deste trabalho foi avaliar a correlação entre a abundância de Li, idade e massa. Os espectros de alta qualidade (R ≃ 115 000; 270 ≤ SNR ≤ 1000) utilizados foram observados com o ESO/HARPS. Os parâmetros atmosféricos das estrelas foram encontrados através da imposição dos equilíbrios de excitação e ionização de linhas de ferro, e as abundâncias de Li foram determinadas via síntese espectral da linha de ^{7}Li em 6707.8 Å. A análise conjunta de 151 estrelas de tipo solar confirma a forte correlação entre abundância de Li e idade reportada por outros trabalhos. A massa e o tamanho do envelope convectivo também parecem estar conectados à abundância de Li, mas com menor significância. Foi encontrada também uma correlação entre a presença de planetas e baixas abundâncias de Li com alta significância em uma amostra de 192 estrelas.

Keywords. Stars: abundances – Stars: evolution – Stars: solar-type – Techniques: spectroscopic

1. Introduction

Lithium (Li) is an important element for stellar astrophysics due to its fragility. It is destroyed at a temperature of 2.5×10^6 K, which is easily reached in the interior of stars. The base of the convective zone of main sequence solar-type stars does not reach a temperature above $\sim 2 \times 10^6$ K. Thus, since the standard stellar model does not consider any mixing processes besides convection, the Li abundance of a single solar-type star should not change as the star evolves along the main sequence.

However, these stars present a decay of Li abundance with stellar age (Carlos et al. 2019), indicating the existence of non-standard transport mechanisms. Many possible mechanisms were invoked, but despite years of theoretical effort, there is still no model capable of explaining every characteristic regarding Li abundance.

Based on this, our goal was to determine what other factors besides age affect A(Li) and quantify this dependence.

2. Methods

Our sample consisted on 74 nearby solar twins and analogs (published in Rathsam et al. 2023) plus 79 solar twins from Carlos et al. (2019). The stars have solar metallicity (within ± 0.15 dex) and are restricted to a mass range between 0.85 and 1.10 $M_\odot$.

We employed high-quality HARPS spectra (R ≃ 115 000; 270 ≤ SNR ≤ 1000) taken from ESO's public database and performed our data reduction (Doppler correction, combination and normalization of spectra) with IRAF.

To find the atmospheric parameters, we measured 118 Fe I and II lines via the line-by-line differential method (Bedell et al. 2014) and applied the spectroscopic equilibrium with the code q^2 (Ramírez et al. 2014). The masses and ages were found via a probability distribution calculated by q^2. The Li abundances were determined via spectral synthesis of the 6707.8 Å line with the code MOOG (Sneden 2023), as shown in Fig. 1. Convective masses were found via interpolation based on theoretical values from Spada et al. (2017).

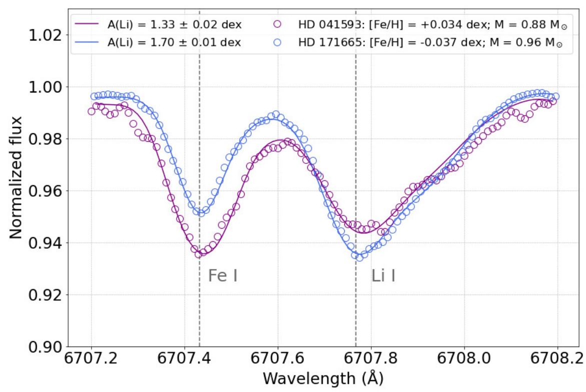

FIGURE 1. Example of the spectra of two stars with similar age but different mass, HD 041593 ($4.5^{+0.9}_{-2.2}$ Gyr) and HD 171665 ($4.8^{+0.4}_{-0.2}$ Gyr). Open circles are the observed spectrum and the solid line is the synthetic spectrum.

3. Results

Our results show a strong trend of lower A(Li) with larger age, but with a much larger scatter than in the sample of solar twins from Carlos et al. (2019) (Fig. 2 in Rathsam et al. 2023). In particular, low-mass stars appear more Li-depleted.

To evaluate the effect of age in A(Li) for solar twins, we selected stars with masses between 0.98 and 1.02 $M_\odot$ and performed an orthogonal distance regression, presented in Fig. 2. The resulting fit shows a strong correlation, with a significance of 14-σ.

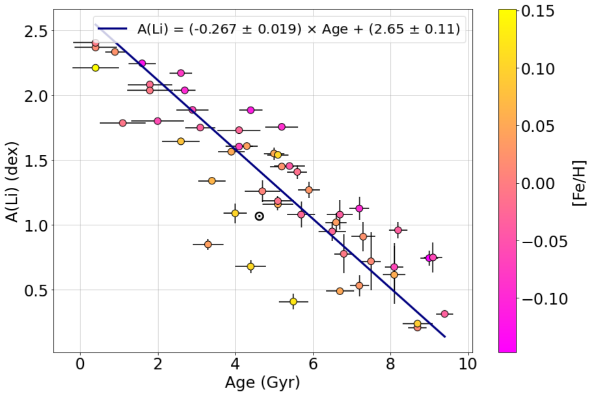

FIGURE 2. Li abundance as a function of age for our solar twin stars ($0.98 \leq M/M_\odot \leq 1.02$), color-coded by [Fe/H].

The stars in our sample show lower A(Li) for lower mass or higher convective mass. This is consistent with what is predicted, since low-mass stars present deeper convective envelopes and are expected to burn more Li. To quantify the influence of mass and convective mass on the Li abundance, we fitted the residuals of the relation found for solar twins (Fig. 2) as a function of mass and the ratio of convective mass over mass for our entire dataset. The results are presented in Figs. 3 and 4, and show that while age is still the most important parameter governing A(Li), mass and convective mass also play a role (with a significance of 2-σ for mass and 5-σ for conv. mass/mass).

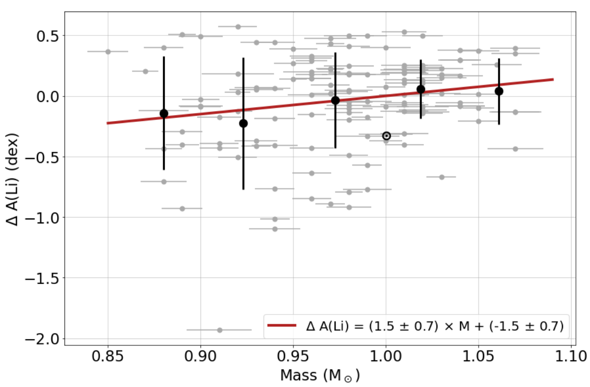

FIGURE 3. Residuals of A(Li) as a function of mass. Gray symbols represent our entire dataset, while black symbols show the average mass and Li residual for each 0.05 $M_\odot$ bin.

Finally, to test whether planet-host stars are more Li-depleted (which could be related to the process of formation of planetary systems, Meléndez et al. 2009), we included in our sample the stars from Martos et al. (2023). Out of 192 stars, 36 had confirmed orbiting planets. We then compared the Li abundance of planet hosts with the average or median abundance of non-hosts "twin" stars (Fig. 5, see caption) and found that planet-hosts appear more Li depleted by ~ 0.2 dex, with a significance above 99% for our results (estimated via a t-test).

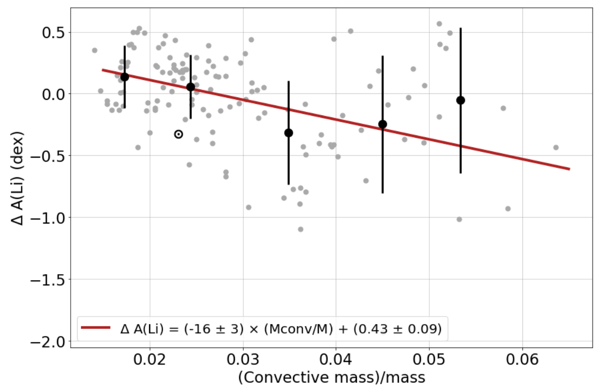

FIGURE 4. Residuals of A(Li) as a function of (convective mass)/mass. Gray symbols represent our entire dataset, and black symbols show the average (convective mass)/mass and Li residual for each 0.01 bin.

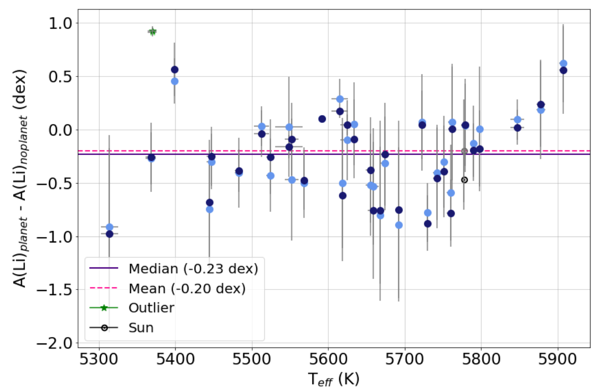

FIGURE 5. Difference between the Li abundance of planet host stars and the median (dark blue) or average (light blue) Li abundance of stars without planets of similar parameters (age ± 0.5 Gyr; mass ± 0.1 $M_\odot$; [Fe/H] ± 0.2 dex) for the stars in our combined sample and the sample from Martos et al. (2023). Error bars on the Y axis represent the standard deviation of the Li abundance of stars without planets for points calculated using the average A(Li) of non-planet hosts or the MAD (median absolute deviation) equivalent of the standard deviation ($\sigma_{MAD} = 1.4826 \times MAD$) for points calculated using the median A(Li) of stars without planets. The solid line indicates the median difference using the median A(Li) of non-planet hosts and the dashed line is the average difference adopting the average A(Li) of stars without planets

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