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Lithium depletion in solar-type stars

Anne Rathsam[1], Jorge Meléndez[1], & Gabriela Carvalho Silva[1]

[1] Instituto de Astronomia, Geofísica e Ciências Atmosféricas - Universidade de São Paulo, Brazil
e-mail: annerathsam@usp.br

Abstract. The main goal of the work is to study the correlation between lithium abundance, age, and mass in a sample composed of 191 main sequence solar analogs, to obtain valuable information concerning the mixing mechanisms occurring in the stellar interior. The results show that age is the main factor affecting lithium abundances. Mass and the convective mass ratio also present correlations with strong significances, which increase as we expand the mass coverage of the analyzed sample.

Resumo. O principal objetivo do trabalho é estudar a correlação entre abundância de lítio, idade e massa em uma amostra composta por 191 estrelas análogas solares de sequência principal, para obter informações valiosas sobre processos de mistura de material que ocorrem no interior estelar. Os resultados mostram que a idade é o principal fator que influencia as abundâncias de lítio. Massa e a razão de massa convectiva também apresentam correlações com fortes significâncias, que aumentam conforme o intervalo de massa da amostra analisada é expandido.

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

1. Introduction

Lithium (Li) is a relevant element for stellar astrophysics because t is destroyed at the relatively low temperature of 2.5×10^6 K, which is easily reached in the interior of stars. In main sequence solar-type stars, the base of the convective zone does not reach a temperature above $\sim 2 \times 10^6$ K. Therefore, since the standard stellar model does not consider any mixing processes besides convection, the Li abundance of a single solar-type star should be constant along the evolution of the star on the main sequence.

However, these stars present a smooth decay of Li abundance with stellar age (Monroe et al. 2013; Carlos et al. 2019), indicating that Li is being taken below their convective regions, into depths with high enough temperature to deplete it. So far, many possible mechanisms were invoked in the literature, such as convective overshooting (Xiong & Deng 2009), convective settling (Andrássy & Spruit 2015), atomic diffusion (do Nascimento et al. 2009), rotation-induced mixing (Charbonnel, Vauclair & Zhan 1992; Pinsonneault 1994), or mixture due to gravity waves in the stellar interior (Charbonnel & Talon 2005). However, despite years of theoretical effort, there is still no model capable of explaining every characteristic regarding Li abundance in different types of star.

Besides age, there are other parameters that may affect Li abundance, such as stellar mass and metallicity, which are directly related to the size of the convective envelope. Both metal rich and low-mass stars present deeper convection zones, and we expect these stars to burn more Li.

In this work, our goal is to evaluate the dependence of A(Li) with different stellar parameters, with a special focus on mass. Thus, we aim to provide data for the development and improvement of non-standard stellar interior models.

2. Methodology

The spectra analyzed for all our stars was taken from ESO's (European Southern Observatory) public database[1], observed with the HARPS (High Accuracy Radial Velocity Planet Searcher) spectrograph. The initial query was for individual SNRs (signal-to-noise ratios) ranging between 20 (to avoid noisy individual spectra) and 370 (to ensure they would not be saturated), with a final goal of achieving a combined spectra with SNR between 250 and 1000. We also obtained HARPS spectra for the Sun, reflected in the surfaces of the Moon and the asteroid Vesta. Details of the Doppler correction, combination, and normalization of the spectra can be found in Rathsam et al. (2023).

To find the atmospheric parameters (T_{eff}, [Fe/H], log g and microturbulence velocity), we measured 117 Fe I and Fe II lines by hand using `IRAF`[2] and performed spectroscopic equilibrium with the code `q`^{2} ((*qoyllur-quipu*[3], Ramírez et al. 2014), adopting the line-by-line differential spectroscopic method with the Sun as the reference star (Bedell et al. 2014).

Our masses and ages are the most probable ones from a probability distribution calculated by q^2. This probability distribution is generated through the comparison of "observed" ((T_{eff}, [Fe/H], M_V from V magnitudes and Gaia DR3 parallaxes) and "theoretical" parameters from Yonsei-Yale isochrones (Yi et al. 2001; Kim et al. 2002).

Lithium abundances were found via spectral synthesis of the 6707.8 Å line with the 1D LTE `MOOG` code (Sneden 2023). An example of the synthesis can be seen in Figure 1. The abundances were corrected for NLTE effects according to the INSPECT[4] database (Lind et al. 2009).

3. Previous results

So far, we have analyzed a combined sample of 151 stars (which includes the solar twins from Carlos et al. 2019), shown in Figure 2. These stars have masses ranging from 0.85 to 1.10 $M_\odot$ and [Fe/H] within ± 0.15 dex. This analysis was presented in Rathsam et al. (2023).

[1] ESO Science Archive Facility, http://archive.eso.org/.

[2] Image Reduction and Analysis Facility, https://iraf-community.github.io/.

[3] q^2 code, https://github.com/astroChasqui/q2.

[4] INSPECT database, http://www.inspect-stars.com/.

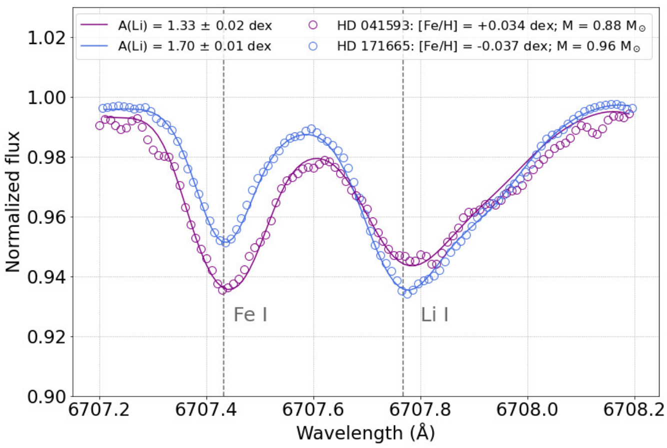

Figure 1. Example of synthesis of the Li 6707.8 Å line for the stars HD 041593 and HD 171665. Open circles show the observed spectra, while the solid lines show the synthetic spectra.

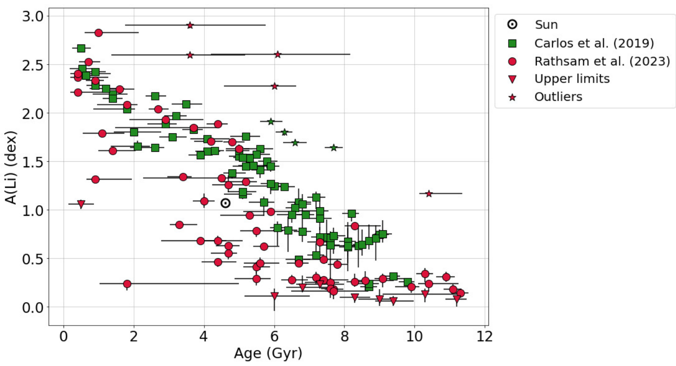

Figure 2. A(Li) versus age for the sample analyzed in Rathsam et al. (2023).

A Li abundance versus age fit performed for solar twins (stars with masses within ± 0.02 $M_{\odot}$ from solar), shown in Figure 3 (from Rathsam et al. 2023), reveals a linear correlation between these parameters with a significance of 14-σ.

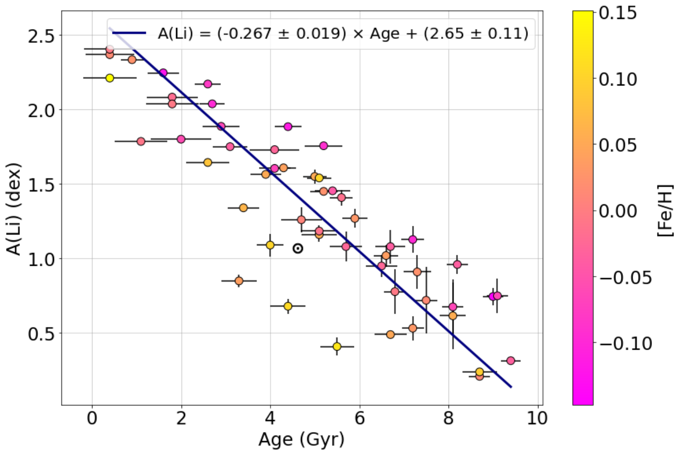

Figure 3. A(Li) versus age fit for solar twins from Rathsam et al. (2023).

To quantify the correlation with mass and the ratio (convective mass)/mass, we performed fits of the residuals of the relation found for solar twins as a function of both parameters for our entire sample. The fits are shown in Figures 4 and 5, taken from (Rathsam et al. 2023). The fits revealed a correlation with a significance of 2-σ for stellar mass and 5-σ for (convective mass)/mass.

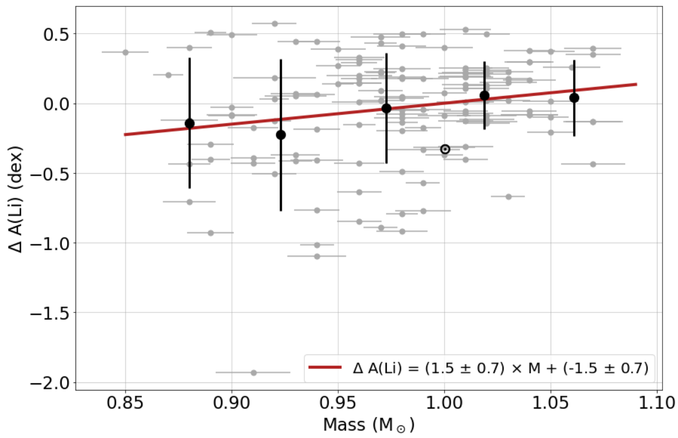

Figure 4. Residuals of A(Li) as a function of mass. Figure from Rathsam et al. (2023).

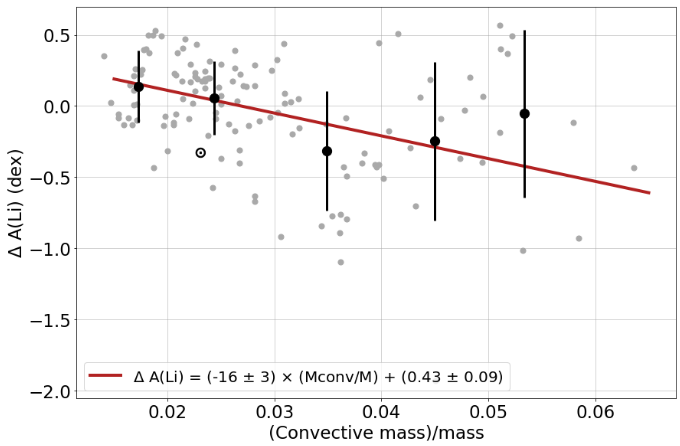

Figure 5. Residuals of A(Li) as a function of (convective mass)/mass. Figure from Rathsam et al. (2023).

4. Updated results

To expand our analysis of the effect of stellar mass and convective mass ratio on the Li abundance of solar-type stars, we selected a sample of 40 stars with the same range in [Fe/H] but with masses between 1.05 and 1.15 $M_{\odot}$. Our new combined sample is shown in Figure 6. The new stars, that have higher masses than the rest of the sample, tend to have larger contents of Li, as expected due to their shallower convective zones. However, the effect of age is still visible – even in higher-mass stars, older stars have depleted more Li.

Figure 7 shows A(Li) plotted against the effective temperature for our entire sample. It can be seen that the hottest stars from our sample have similar Li abundances, which is expected – the work of Boesgaard & Tripicco (1986) on the (~solar metallicity) Hyades cluster was the first to identify that F-type stars with temperatures between 6200 and 7000 K present an abrupt decay of their Li abundances in comparison with stars hotter or

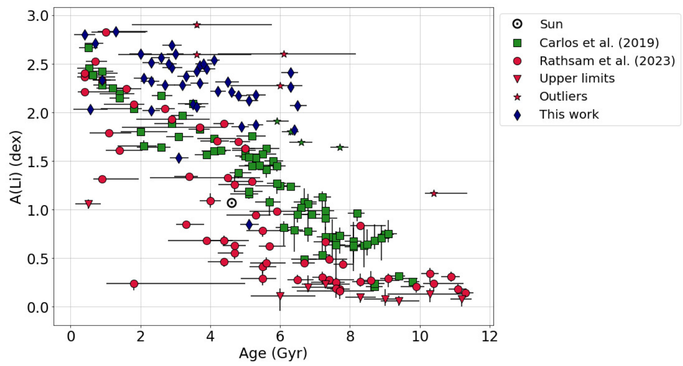

Figure 6. A(Li) versus age for the analyzed sample, including the 40 new stars with supersolar masses.

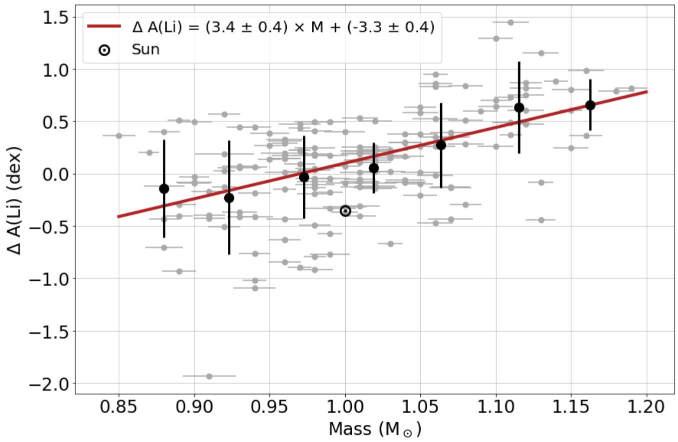

Figure 8. Residuals of A(Li) as a function of mass for our entire sample.

colder than this interval (the so-called lithium dip or Boesgaard dip). Nevertheless, between 6200 K and temperatures slightly larger than solar, we observe a plateau in A(Li), indicating that these stars suffer lighter Li depletion. This plateau is also seen in Figure 7, in a similar effective temperature range.

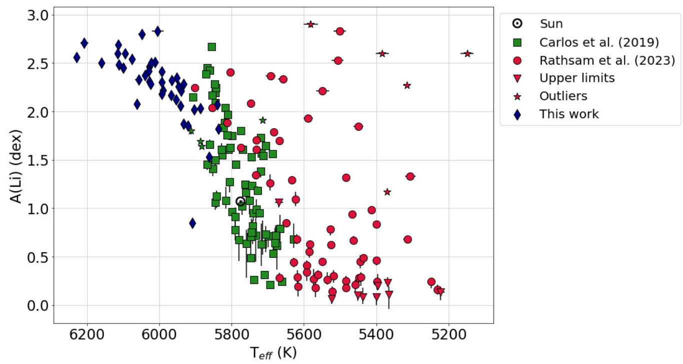

Figure 7. A(Li) versus effective temperature for the analyzed sample.

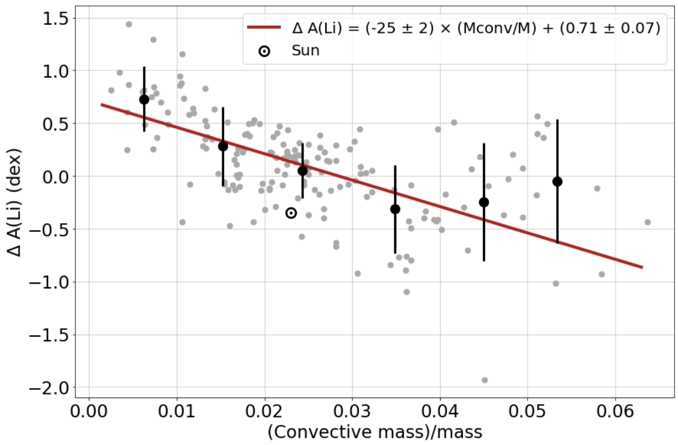

Figure 9. Residuals of A(Li) as a function of (convective mass)/mass for our entire sample.

Figures 8 and 9 show the re-fitted residuals of the A(Li)-age relation from Figure 3 for our entire sample. With the expansion toward stars with higher masses, we find a new significance of 8.5-σ for the correlation between A(Li) and mass and 12.5-σ for the correlation between A(Li) and (convective mass)/mass. As in our previous results, the correlation with the convective mass ratio is stronger, which shows that convective mass is a more important parameter for A(Li) than mass. This stronger correlation is likely the result of the effect of metallicity on the size of the convection region.

5. Conclusions

In this work, we analyzed the correlation between A(Li), mass, and convective mass in an extended main sequence solar-type sample which increased the mass coverage of the sample analyzed in Rathsam et al. (2023) (composed of solar twins and lower-mass stars) toward stars with supersolar masses, up to 1.15 M$_\odot$. The new, more massive stars still present signs of a correlation with age – older stars present lower Li abundances, as expected.

Additionally, with the expansion of the sample, the significances of the correlations between A(Li), stellar mass, and (convective mass)/mass have increased from 2-σ to 8.5-σ in the case of mass and from 5-σ to 12.5-σ in the case of (convective mass)/mass. The higher significance of the convective mass ratio reflects the fact that besides mass, [Fe/H] also plays a role in the size of the convection region, thus affecting the depth that Li can reach in the stellar interior.

The next steps of our work include increasing the mass interval of the sample toward even higher stellar masses and expanding the [Fe/H] coverage. With this, we will be able to perform a joint analysis of the effects of mass and metallicity on Li depletion. Additionally, other parameters may be explored, such as rotation velocity and stellar activity.

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References

Andrássy R. & Spruit H. C. 2015, A&A, 579, A112
Bedell M., Meléndez J., Bean J. L., Ramírez I., Leite P. & Asplund M. 2014, ApJ, 795, 23
Boesgaard A. M. & Tripicco M. J. 1986, ApJ, 302, L49
Carlos M. et al., 2019, MNRAS, 485, 4052
Charbonnel C., Vauclair S., & Zahn J. P. 1992, A&A, 255, 191
Charbonnel C. & Talon S. 2005, Sci, 309, 2189
do Nascimento J. D., Jr., Castro M., Meléndez J., Bazot M., Théado S., Porto de Mello G. F., & de Medeiros J. R. 2009, A&A, 501, 687
Kim Y. C., Demarque P., Yi S. K., & Alexander D. R. 2002, ApJS, 143, 499
Lind K., Asplund M., & Barklem P. S. 2009, A&A, 503, 541

Monroe T. R. et al. 2013, ApJ, 774, L32
Pinsonneault M. H., 1994, in Caillault J.-P., ed., ASP Conf. Ser. Vol. 64, Cool Stars, Stellar Systems, and the Sun. Astron. Soc. Pac., San Francisco, p. 254
Ramírez I. et al. 2014, A&A, 572, A48
Rathsam A., Meléndez J., & Carvalho-Silva G. 2023, MNRAS, 525, 4642
Sneden C. 1973, ApJ, 184, 839
Xiong D. R. & Deng L., 2009, MNRAS, 395, 2013
Yi S., Demarque P., Kim Y. C., Lee Y. W., Ree C. H., Lejeune T., & Barnes S., 2001, ApJS, 136, 417