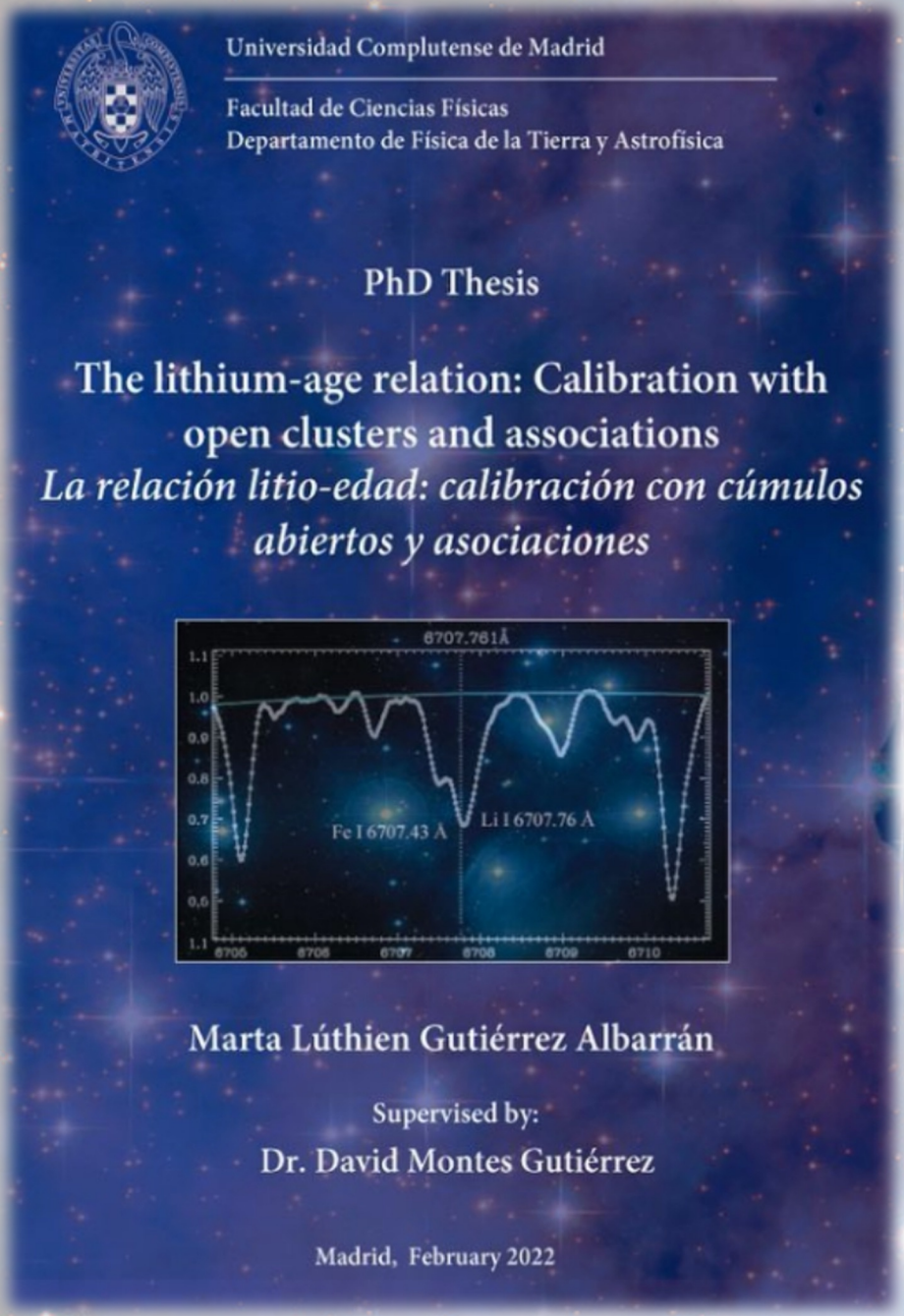


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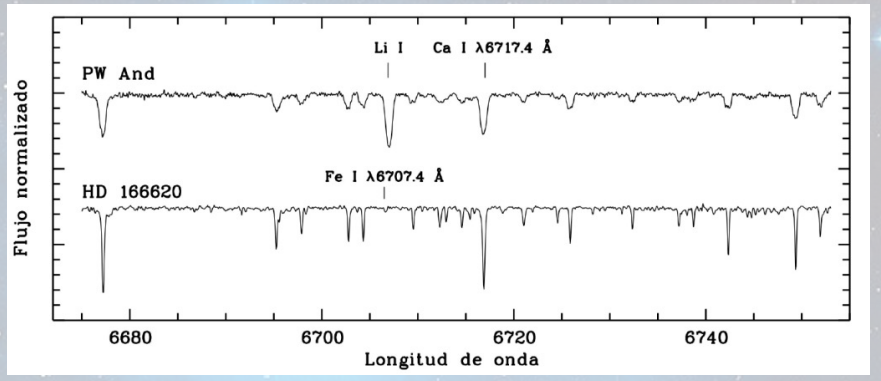
La relación Li-edad

Dra. Marta Lúthien Gutiérrez Albarrán
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XII Jornadas de Introducción a la Investigación, 22-26 abril 2024

Introduction: Lithium as an age calibrator

❖ Lithium (Li I spectral line at 6708 Å) is a **very sensitive indicator of youth in late-type FGKM stars and a useful tracer of stellar evolution.**

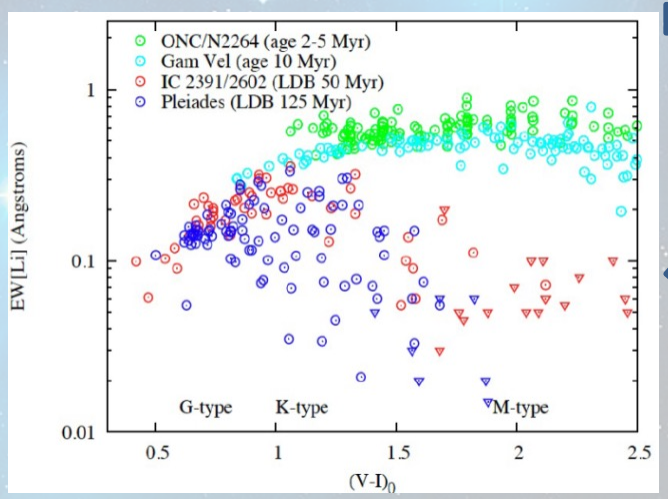


Li I line at 6707.76 Å In the spectrum of a young star (López-Santiago et al, 2003)

❖ Li is strongly **age and mass-dependent**, but also shows a **complex pattern depending on several parameters** (**rotation, chromospheric activity, metallicity**, mixing mechanisms,…) → We can **calibrate** these effects by analysing **open clusters and associations**.

➢ **Surface abundance of Li is slowly being depleted** over time in **FGKM** stars. **Li depletion increases with decreasing mass**.

❖ We have studied **Li as an age indicator for pre- and main-sequence FGKM stars** in **42 open clusters** (ages from **1-3 Myr** to **4.5 Gyr**) analysed using **GES iDR6 and *Gaia* EDR3 data**.



EW(Li) as a function of colour and spectral type for several clusters, from Soderblom et al. (2014).

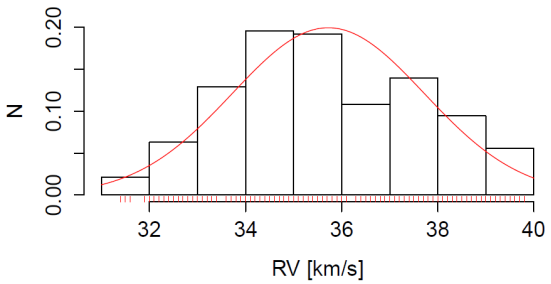
Data: Cluster sample

- ***Young (1-50 Myr)***
- ***Intermediate-age (50-700 Myr)***
- ***Old (>700 Myr)***

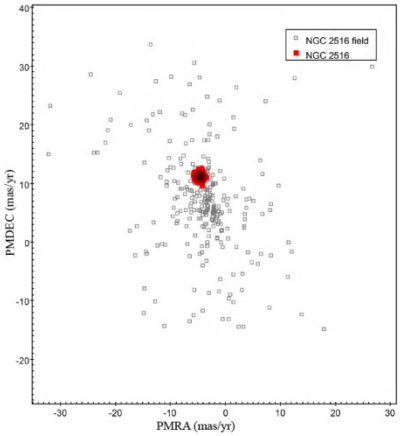
Cluster name	Age (Myr)	E(B-V)[a] (dex)	Distance (kpc)
NGC 6530	1–2	0.44 ± 0.10	1.33
ρ Oph	1–3	0.76 ± 0.13	0.13 ± 0.01
Trumpler 14	1–3	0.61 ± 0.10	2.90
Cha I	2	0.18 ± 0.08	0.16 ± 0.02
NGC 2244	4	0.49 ± 0.09	1.59
NGC 2264	4	0.05 ± 0.05	0.76
λ Ori	6	0.09 ± 0.04	0.41
Col 197	13	0.64 ± 0.07	0.80–0.90
γ Vel	10–20	0.04 ± 0.03	0.35–0.40
NGC 2232	18–32	0.04 ± 0.03	0.32
NGC 2547	20–45	0.06 ± 0.03	0.36 ± 0.02
IC 2391	36 ± 2 [c]	0.03 ± 0.01	0.16 ± 0.01
IC 2602	35 ± 1 [c]	0.04 ± 0.02	0.15 ± 0.01
IC 4665	38 ± 3 [c]	0.15 ± 0.02	0.36 ± 0.01
NGC 2451 B	39 ± 1 [c]	0.10 ± 0.03	0.36
NGC 2451 A	44 ± 2 [c]	0.02 ± 0.02	0.19

Cluster name	Age (Myr)	E(B-V)[a] (dex)	Distance (kpc)
NGC 6405	94	0.14 ± 0.04	0.46
Blanco 1	94 ± 5 [c]	-0.01 ± 0.03	0.23–0.24
NGC 6067	120	0.34 ± 0.04	1.4–1.7
NGC 6649	120	1.43 ± 0.05	1.8 ± 0.1
NGC 2516	125–138	0.11 ± 0.03	0.41
NGC 6709	173 ± 34 [c]	0.27 ± 0.02	1.1
NGC 6259	210	0.63 ± 0.09	1.9
NGC 6705	280	0.40 ± 0.06	1.88
Berkeley 30	300	0.51 ± 0.04	4.7–4.9
NGC 6281	314	0.18 ± 0.02	0.47–0.51
NGC 3532	399 ± 5 [c]	0.05 ± 0.02	0.48–0.49
NGC 4815	560	0.70 ± 0.07	2.40–2.90
NGC 6633	575	0.15 ± 0.04	0.39
NGC 2477	700	0.31	1.4
Trumpler 23	800	0.68 ± 0.04	2.20
Berkeley 81	860 ± 100	0.85 ± 0.04	3.00
NGC 2355	900	0.13 ± 0.03	1.80 ± 0.07
NGC 6802	900	0.79 ± 0.06	1.80
NGC 6005	973 ± 4 [c]	0.49 ± 0.06	2.70
Pismis 18	1200 ± 400	$+0.22 \pm 0.04$	2.20
Melotte 71	1294 ± 89 [c]	0.11	2.2–3.2
Pismis 15	1300	0.56 ± 0.05	2.6–2.9
Trumpler 20	1400	0.37 ± 0.03	3.00
Berkeley 44	1600	0.90 ± 0.07	1.80–3.10
NGC 2243	4000 ± 120	0.04 ± 0.04	4.50
M67	4000–4500	0.059	0.90

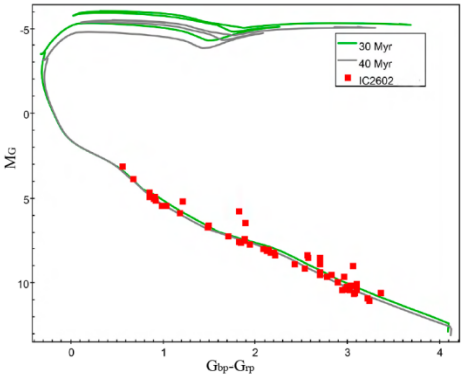
1) Membership analysis to obtain lists of robust cluster candidates



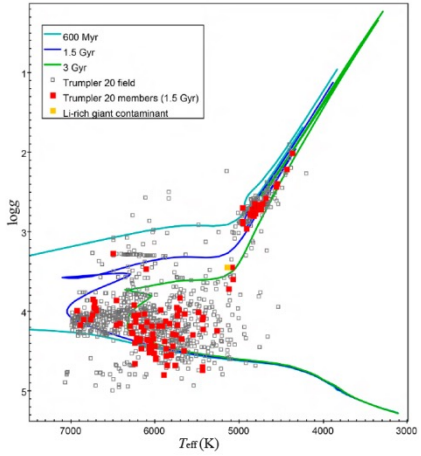
1) Analysis of *RV* distributions

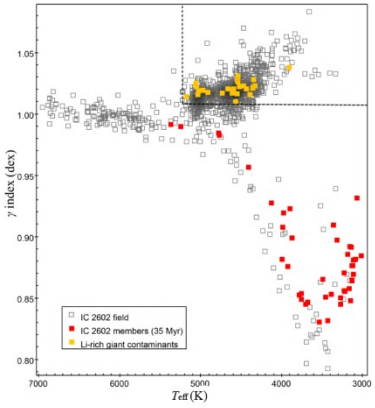


2) *Gaia* astrometry: proper motions and parallax

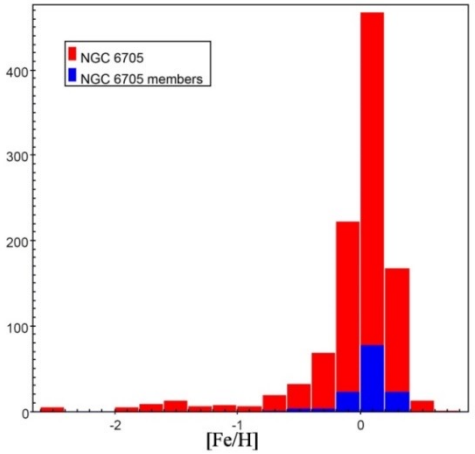


3) *Gaia* photometry (CMDs)

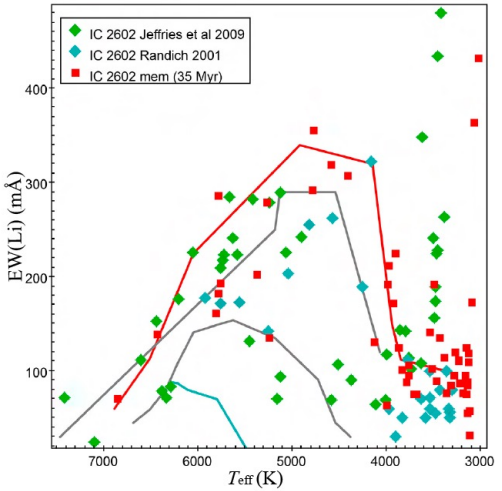




4) Gravity indicators: Kiel diagram and **(γ, $T_{\rm eff}$) plane**



5) [Fe/H] metallicity

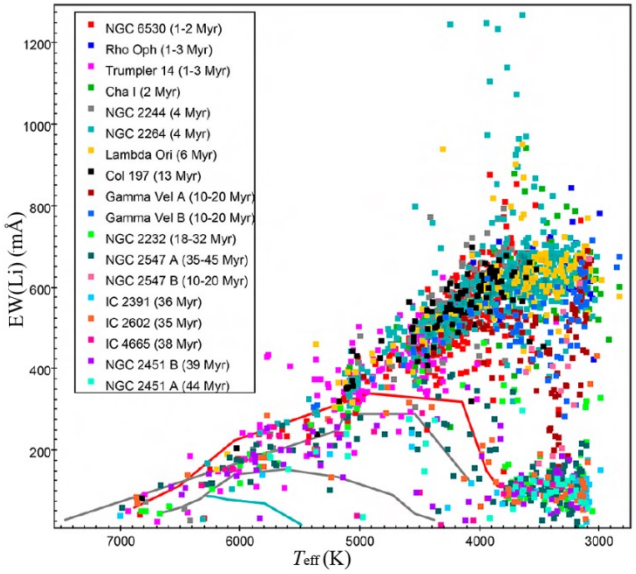


6) Position in *EW*(Li) vs $T_{\rm eff}$ diagram with **empirical envelopes as guide**.

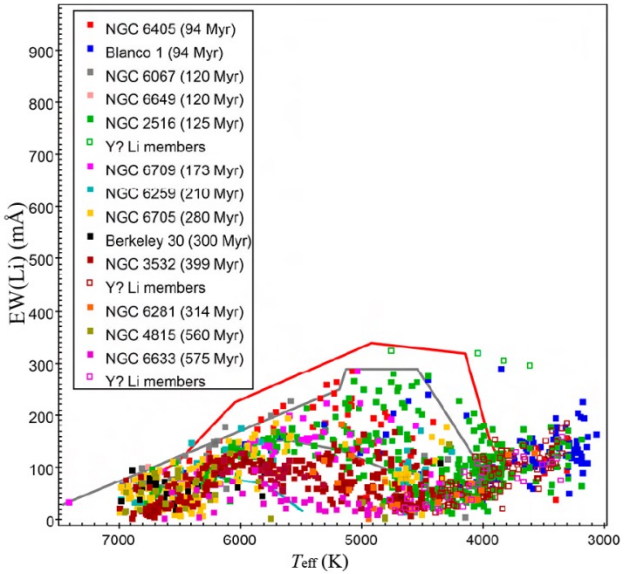
7) *Gaia* DR1, DR2 and EDR3 studies

Final member selections for all target clusters

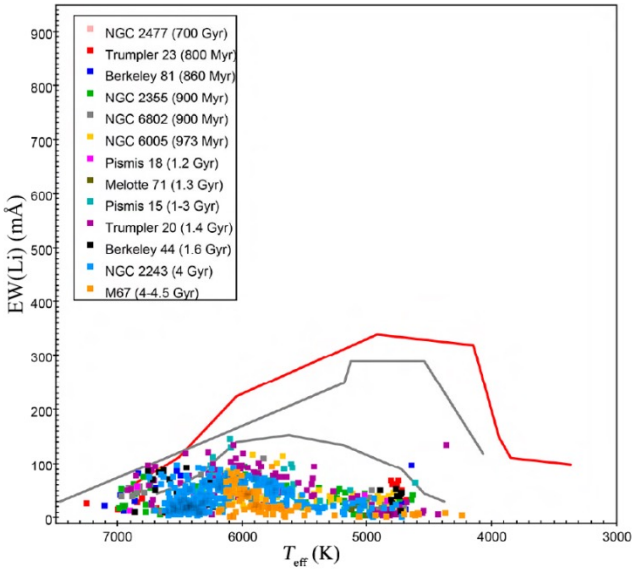
Young clusters (1-50 Myr)



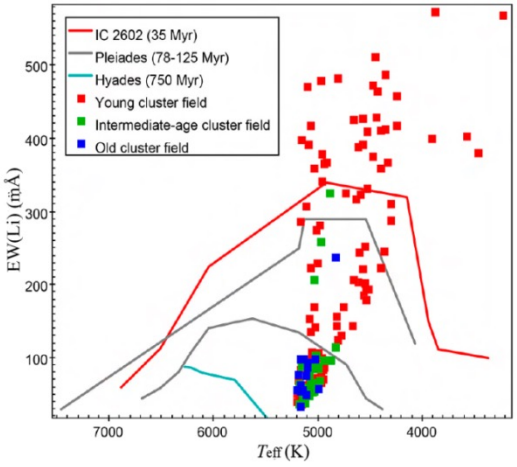
Intermediate–age clusters (50-700 Myr)



Old clusters (>700 Myr)



- Additional result → **Preliminary lists of Li-rich giant contaminants** for **23** target clusters, defined as those giant field outliers with **A(Li) ≥ 1.5**.



Preliminary membership analysis: Paper I (refereed paper in A&A)

A&A 643, A71 (2020)
https://doi.org/10.1051/0004-6361/202037620
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Astronomy & Astrophysics

The *Gaia*-ESO Survey: Calibrating the lithium–age relation with open clusters and associations

I. Cluster age range and initial membership selections★,★★

M. L. Gutiérrez Albarrán[1], D. Montes[1], M. Gómez Garrido[1,2], H. M. Tabernero[1,3], J. I. González Hernández[4,5], E. Marfil[1], A. Frasca[6], A. C. Lanzafame[7,6], A. Klutsch[8,6], E. Franciosini[9], S. Randich[9], R. Smiljanic[10], A. J. Korn[11], G. Gilmore[12], E. J. Alfaro[23], M. Baratella[24], A. Bayo[20,21], T. Bensby[13], R. Bonito[14], G. Carraro[15], E. Delgado Mena[3], S. Feltzing[13], A. Gonneau[12], U. Heiter[11], A. Hourihane[12], F. Jiménez Esteban[16], P. Jofre[22], T. Masseron[4,5], L. Monaco[17], L. Morbidelli[9], L. Prisinzano[14], V. Roccatagliata[18], S. Sousa[3], M. Van der Swaelmen[9], C. C. Worley[12], and S. Zaggia[19]

(Affiliations can be found after the references)

Received 29 January 2020 / Accepted 29 July 2020

ABSTRACT

Context. Previous studies of open clusters have shown that lithium depletion is not only strongly age dependent but also shows a complex pattern with other parameters that is not yet understood. For pre- and main-sequence late-type stars, these parameters include metallicity, mixing mechanisms, convection structure, rotation, and magnetic activity.

Aims. We perform a thorough membership analysis for a large number of stars observed within the *Gaia*-ESO survey (GES) in the field of 20 open clusters, ranging in age from young clusters and associations, to intermediate-age and old open clusters.

Methods. Based on the parameters derived from the GES spectroscopic observations, we obtained lists of candidate members for each of the clusters in the sample by deriving radial velocity distributions and studying the position of the kinematic selections in the EW(Li)-versus-$T_{\rm eff}$ plane to obtain lithium members. We used gravity indicators to discard field contaminants and studied [Fe/H] metallicity to further confirm the membership of the candidates. We also made use of studies using recent data from the *Gaia* DR1 and DR2 releases to assess our member selections.

Results. We identified likely member candidates for the sample of 20 clusters observed in GES (iDR4) with UVES and GIRAFFE, and conducted a comparative study that allowed us to characterize the properties of these members as well as identify field contaminant stars, both lithium-rich giants and non-giant outliers.

Conclusions. This work is the first step towards the calibration of the lithium–age relation and its dependence on other GES parameters. During this project we aim to use this relation to infer the ages of GES field stars, and identify their potential membership to young associations and stellar kinematic groups of different ages.

Key words. open clusters and associations: general – stars: late-type – stars: abundances – techniques: spectroscopic

1. Introduction

Lithium is a very fragile element that is easily destroyed in stellar interiors, burning at temperatures above ~2.5×10^6 K, corresponding to the temperature at the base of the convective zone of a solar-mass star on the zero-age main sequence (ZAMS; Siess et al. 2000). For this reason, lithium is slowly being depleted and its surface abundance decreases over time in solar-type and lower mass stars (Jeffries et al. 2014; Bouvier et al. 2016; Lyubimkov 2016). According to standard stellar models, low-mass stars show lithium depletion increasing with decreasing mass, while stars more massive than the Sun undergo little or no depletion, and very low-mass stars show no depletion at all, given that their central temperature never reaches the Li burning point (Jones et al. 1999). An additional contribution of surface lithium abundance can also be detected for some stars, such as Li-rich giants. Given the low stellar temperatures necessary to destroy lithium in stellar interiors, these Li-rich stars would require extra non-standard mixing mechanisms to account for the additional lithium detected on their surfaces (see Sect. 4).

Because it only survives in the outer layers of a star[1], lithium is a very sensitive tracer of stellar evolution and non-standard mixing mechanisms in stellar interiors (see e.g., Sestito & Randich 2005; Castro et al. 2016), and is particularly relevant for studies of the evolution of low-mass stars and for the determination of the age of stellar clusters. Cluster ages determined in this way are less subject to systematic uncertainties than ages derived from other methods (e.g., Hobbs & Pilachowski 1986; Oliveira et al. 2003; Soderblom et al. 2014).

As most stars do not form individually, but inside clusters and associations, the study of clusters of different ages (from a few Myr to several Gyr) and chemical compositions is essential to understand star formation and evolution. In addition to this, open clusters are very useful tracers when studying the formation and evolution of the Galaxy, especially the spatial

★ Based on observations collected with ESO telescopes at the La Silla Paranal Observatory in Chile, for the *Gaia*-ESO Large Public Spectroscopic Survey (188.B-3002, 193.B-0936).

★★ All tables in Appendix C are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/643/A71

[1] And in fully convective stars the surface abundance of Li is rapidly depleted when the core reaches the Li-burning temperature.

This work has updated and expanded the work already published in Gutiérrez Albarrán et al. (2020) for 20 open clusters with data provided by the iDR4 release of GES.

This first publication is available on A&A: **The *Gaia-ESO* Survey: Calibrating the lithium-age relation with open clusters and associations. I. Cluster age range and initial membership selections (Gutiérrez Albarrán et al. 2020. A&A, 643, A71): 2020A&A...643A..71G**

Final membership analysis: Paper II (refereed paper in A&A)

arXiv > astro-ph > arXiv:2404.08859

Help | A

Astrophysics > Solar and Stellar Astrophysics

[Submitted on 13 Apr 2024]

The Gaia-ESO Survey: Calibrating the lithium-age relation with open clusters and associations. II. Expanded cluster sample and final membership selection

M.L. Gutiérrez Albarrán, D. Montes, H.M. Tabernero, J.I. González Hernández, E. Marfil, A. Frasca, A.C. Lanzafame, A. Klutsch, E. Franciosini, S. Randich, R. Smiljanic, A.J. Korn, G. Gilmore, E.J. Alfaro, T. Bensby, K. Biazzo, A. Casey, G. Carraro, F. Damiani, S. Feltzing, P. François, F. Jiménez Esteban, L. Magrini, L. Morbidelli, L. Prisinzano, T. Prusti, C.C. Worley, S. Zaggia, GES builders

The Li abundance observed in pre-main sequence and main sequence late-type stars is strongly age-dependent, but also shows a complex pattern depending on several parameters, such as rotation, chromospheric activity and metallicity. The best way to calibrate these effects, with the aim of studying Li as an age indicator for FGK stars, is to calibrate coeval groups of stars, such as open clusters (OCs) and associations. We present a considerable target sample of 42 OCs and associations, ranging from 1 Myr to 5 Gyr, observed within the Gaia-ESO survey (GES), and using the latest data provided by GES iDR6 and the most recent release of Gaia that was then available, EDR3. As part of this study, we update and improve the membership analysis for all 20 OCs presented in our previous article. We perform detailed membership analyses for all target clusters to identify likely candidates, using all available parameters provided by GES and based on numerous criteria: from radial velocity distributions, to the astrometry and photometry provided by Gaia, to gravity indicators, [Fe/H] metallicity, and Li content. We obtain updated lists of cluster members for the whole target sample, as well as a selection of Li-rich giant contaminants obtained as an additional result of the membership process. Each selection of cluster candidates was thoroughly contrasted with numerous existing membership studies using data from Gaia to ensure the most robust results. These final cluster selections will be used in the third and last paper of this series, which reports the results of a comparative study characterising the observable Li dispersion in each cluster and analysing its dependence on several parameters, allowing us to calibrate a Li-age relation and obtain a series of empirical Li envelopes for key ages in our sample.

Comments: 83 pages, 246 figures. To be published in A&A, accepted January 27, 2024

Subjects: **Solar and Stellar Astrophysics (astro-ph.SR)**

Cite as: arXiv:2404.08859 **[astro-ph.SR]**

This second publication is currently available on arXiv: **The *Gaia-ESO* Survey: Calibrating the lithium-age relation with open clusters and associations. II. Expanded cluster sample and final membership selection (Gutiérrez Albarrán et al. 2024, A&A, in production): arXiv:2404.08859.**

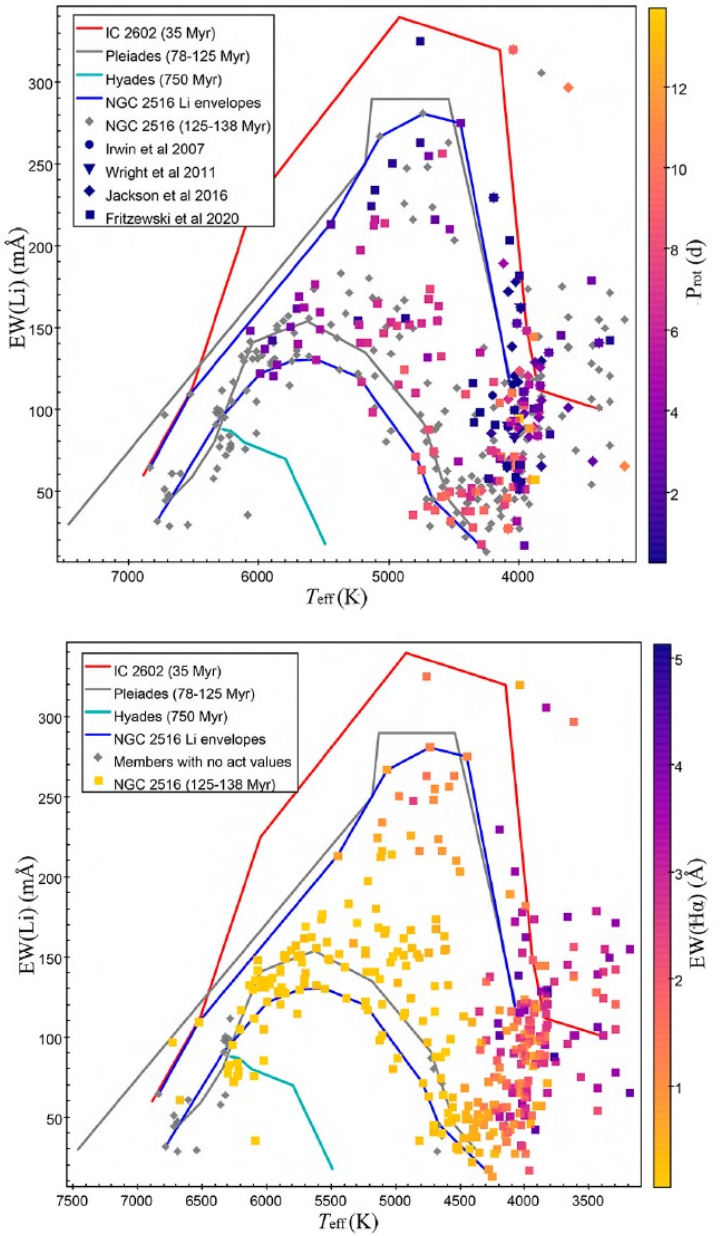
2) Dependence of Li with parameters

❖ **Influence of rotation, activity, accretion** and **metallicity** in the **observable lithium dispersion of the cluster candidates.**

❖ **Rotational velocities (*v*sin*i*), *EW*(Hα) chromospheric activity, accretion indicators**, and **[Fe/H] metallicities** provided by **GES.**

❖ **Rotational periods (P_{rot})** from the literature, including **CoRoT, *Kepler*, K2,** and **TESS** measurements.

❖We confirmed the correlations found in the literature → **Li-rich members tend to be faster rotators and show higher levels of activity**, tracing the upper Li envelopes for each cluster.



EW(Li)-versus-T_{eff} diagram colour-coded by P_{rot} and Hα for NGC 2516 (125-138 Myr).

2) Dependence of Li with parameters

- We have additionally observed slight **effects of [Fe/H] metallicity in the Li depletion of coeval clusters.**

- **Metal-rich clusters would seem to tend to show higher Li abundances than their metal-poor counterparts**.

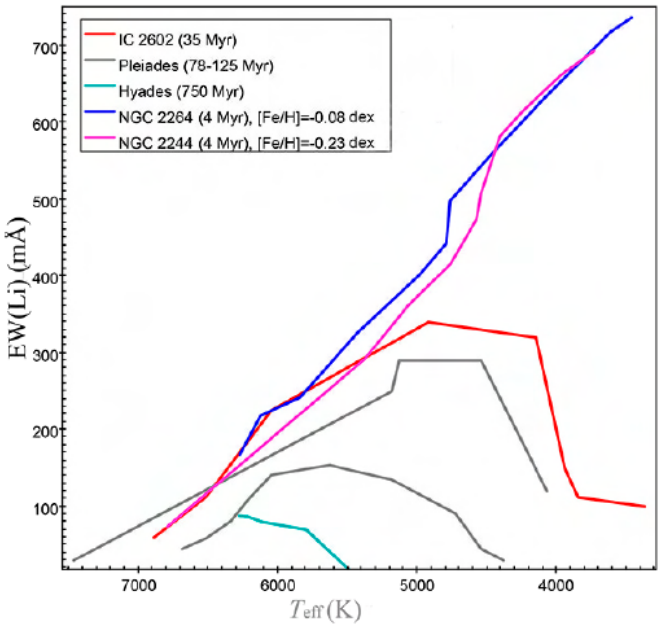


Figure 3.26: EW(Li)-versus-$T_{\rm eff}$ diagram comparing the upper Li envelopes for NGC 2244 (4 Myr, [Fe/H]=−0.23 dex) and NGC 2264 (4 Myr, [Fe/H]=−0.08 dex).

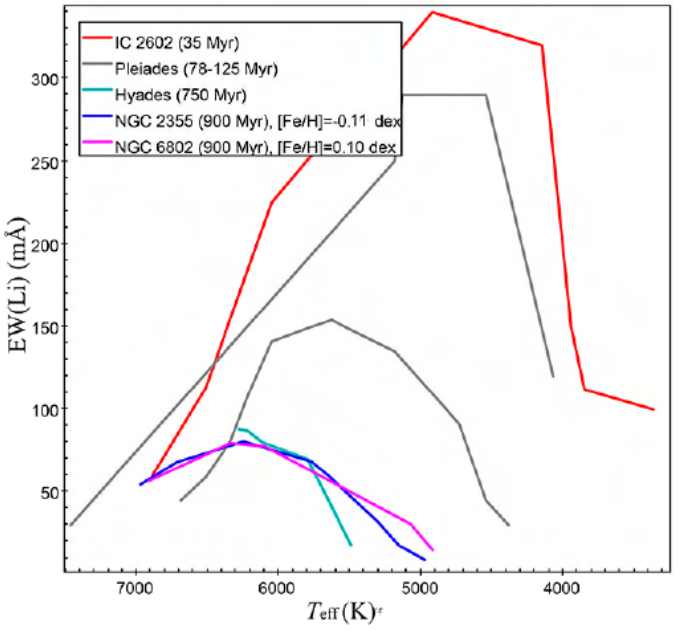


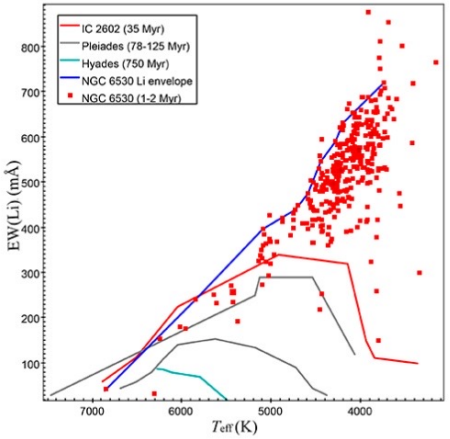
Figure 3.29: EW(Li)-versus-$T_{\rm eff}$ diagram comparing the upper Li envelopes for NGC 2355 (900 Myr, [Fe/H]=−0.11 dex) and NGC 6802 (900 Myr, [Fe/H]=0.10 dex).

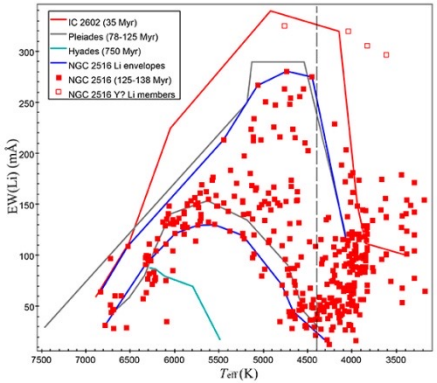
3) Calibration of the Li-age relation: Empirical Li envelopes

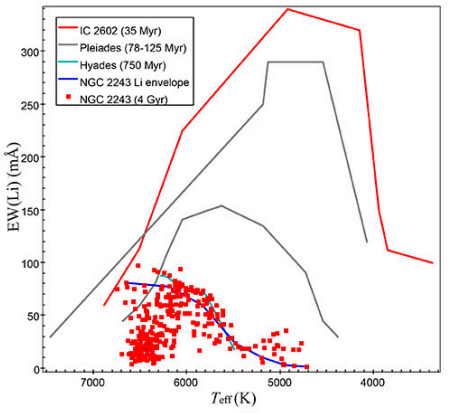
- **Empirical Li envelopes for key ages from 1–3 Myr to 4–4.5 Gyr**, tracing the **upper and/or lower limit of *EW*(Li) for a given T_{eff}** and **delimiting the regions populated by the cluster candidates** *(see examples for NGC 6530 (1-2 Myr), NGC 2516 (125-138 Myr), and NGC 2243 (4 Gyr), right)*

- **Li envelopes for 27 out of 42 sample clusters (64%)**. Wider age range than formerly available in the literature.

- **Preliminary characterization of the LDB for clusters with ages in the 10–600 Myr range**. **T_{eff} values** given by **evolutionary models** of **Baraffe et al. (2015)**, as dotted lines *(IC 2602, below)*.







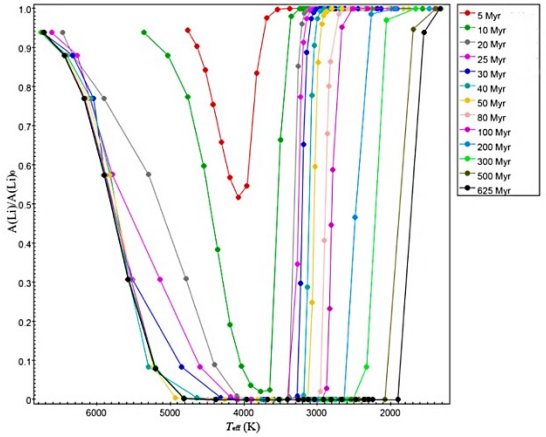
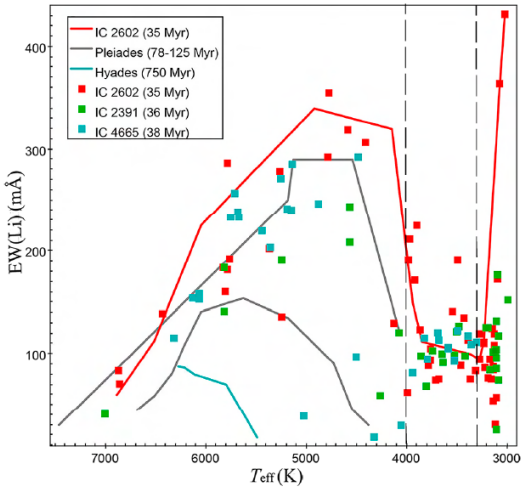
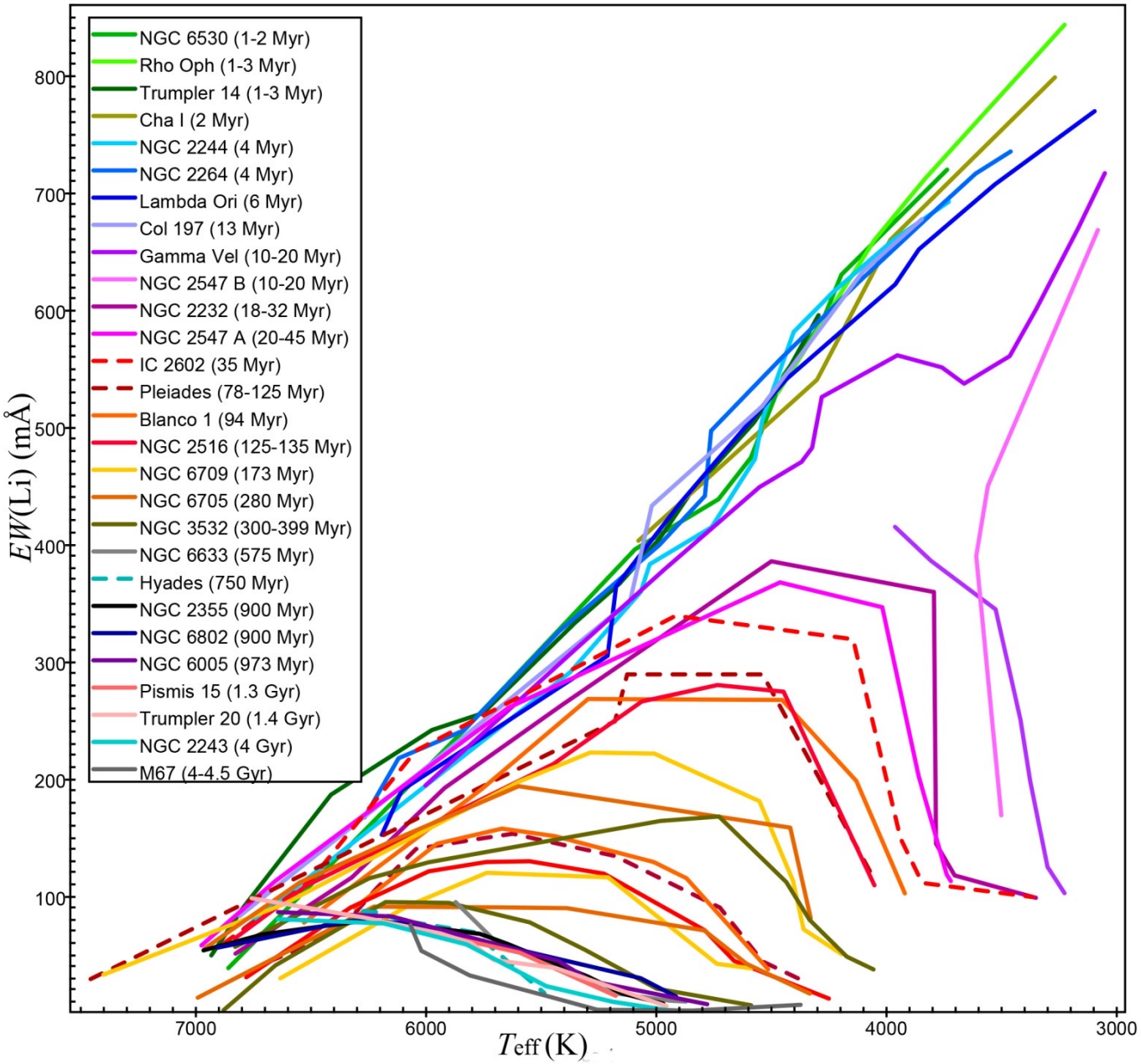


Figure 4.8: Evolutionary tracks from Baraffe et al. (2015) for an age range of 5–625 Myr, where $A(Li)/A(Li)_0$ is the ratio of surface Li abundance to initial abundance.



The Li-age relation: Final empirical Li envelopes



***EW*(Li) vs T_{eff} diagrams** with the **empirical Li envelopes obtained for 27 out of the 42 clusters in the sample**.

Future work: These empirical Li envelopes can be used to **estimate age ranges** for **GES iDR6 MW field stars**, whose age is still unknown.

Qualitative Li envelopes → automated method to create **quantitative envelopes for more precise age estimates.**

Calibration of the Li-age relation: Paper III (submitted to A&A, in revision)

Astronomy & Astrophysics manuscript no. output
October 25, 2023
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The *Gaia*-ESO Survey: Calibrating the lithium–age relation with open clusters and associations ⋆

III. Calibration and dependence with stellar parameters.

M.L. Gutiérrez Albarrán[1], D. Montes[1], H.M. Tabernero[1,2], J.I. González Hernández[3,4], E. Marfil[1,5], A. Frasca[6], A. C. Lanzafame[7,6], A. Klutsch[8,6], E. Franciosini[9], S. Randich[9], R. Smiljanic[10], A. J. Korn[11], G. Gilmore[12], E. J. Alfaro[13], T. Bensby[16], K. Biazzo[17], A. Casey[20], G. Carraro[23], F. Damiani[15], S. Feltzing[16], P. François[22], F. Jiménez Esteban[14], L. Magrini[9], L. Morbidelli[9], L. Prisinzano[15], T. Prusti[21], C. C. Worley[19], S. Zaggia[18] and GES builders

(Affiliations can be found after the references)

Received , 2023; accepted ,

ABSTRACT

Context. The Li abundance observed in pre- and main-sequence late-type stars is strongly age-dependent, but also shows a complex pattern depending on several parameters, such as rotation, chromospheric activity and metallicity. The best way to calibrate these effects is to calibrate coeval groups of stars, such as open clusters and associations.
Aims. We made use of the lists of candidate members obtained in the companion paper to this work (Gutiérrez Albarrán et al. 2023) for a target sample of 42 open clusters, ranging from 1 Myr to 5 Gyr and observed within the *Gaia*-ESO survey (GES), with the aim of studying Li as an age indicator and deriving an empirical Li-age relation for FGK late-type stars.
Methods. We conducted a comparative study that allowed us to quantify the observable Li dispersion in each cluster, and analyse in detail its dependence with several other stellar parameters derived from GES: rotation, chromospheric activity (Hα), accretion processes, and metallicity. We also compared our analyses with various correlations and findings of earlier publications, from the Li-rotation and Li-activity connections, to the effects of metallicity in the Li depletion of coeval clusters.
Results. The identification of likely candidates for all clusters and the characterization of their properties allowed us to calibrate a Li-age relation and obtain a series of empirical Li envelopes for key ages in our sample. We also constrained the Li depletion boundary for those clusters in the 15–500 Myr age range with the aid of several models.
Conclusions. This work, additionally presented in full as a thesis in Gutiérrez Albarrán (2022), has concluded our aim to analyse the dependence of Li depletion on several GES parameters and calibrate a preliminary empirical Li–age relation. As part of our future work, such a calibration will allow us to estimate age ranges for GES field stars, and identify their potential membership to young associations and stellar kinematic groups of different ages.

Key words. Galaxy: open clusters and associations: general – Stars: late-type – Stars: abundances – Techniques: spectroscopic – Stars: rotation – Stars: activity

1. Introduction

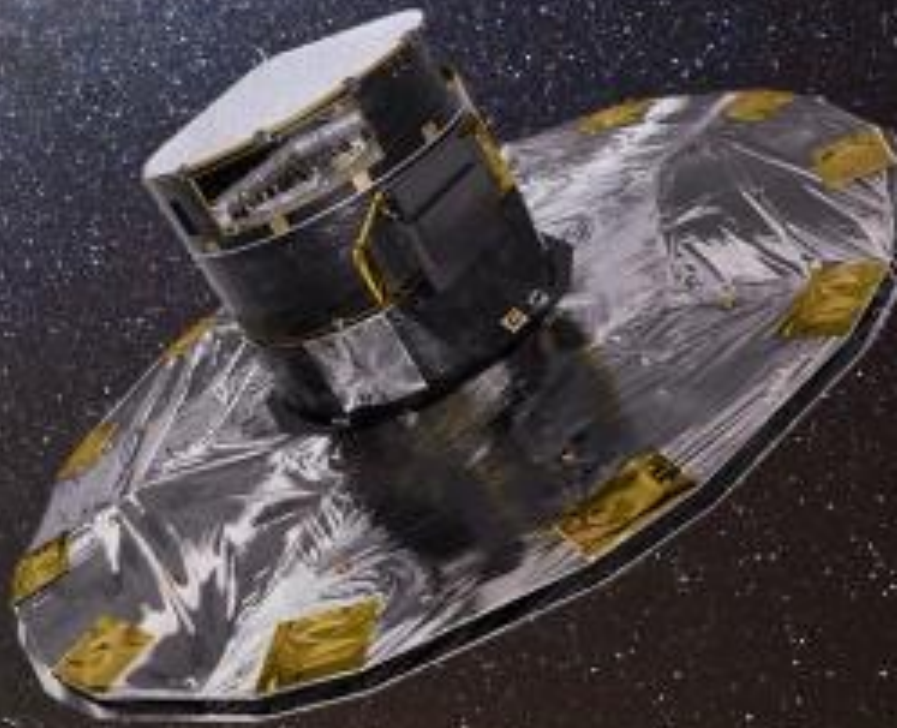
While standard models of stellar evolution, with convection as the only mixing mechanism, predict that stellar Li abundances should only be a function of effective temperature, mass and age (e.g., Soderblom et al. 1990; Soderblom 2010; Dumont et al. 2021b; Randich & Magrini 2021), the Li abundances observed in various studies for solar and late-type stars in open clusters (OCs) of different ages have shown a significant spread in Li abundance at a given colour (or mass) which could not be attributed to observational errors (e.g., Soderblom et al. 1993; Jeffries et al. 2014; Barrado et al. 2016; Bouvier et al. 2018). Observations have shown a complex pattern of Li depletion for PMS (pre-Main Sequence) and MS (Main Sequence) stars that is not a simple function of mass and stellar age only, but also depends on a series of other factors and parameters, such as rotation, activity, metallicity, accretion, magnetic activity, and convection structure (e.g., Randich et al. 2002; Pallavicini et al. 2005; Bouvier 2008; Soderblom et al. 2014; Barrado et al. 2016; Castro et al. 2016; Lyubimkov 2016; Randich & Magrini 2021). This indicates the presence of a variety of additional non-standard mixing processes (in addition to convection) that would account for the observed enhanced Li spread in FGK stars, such as rotational mixing, convective overshooting, mass loss through stellar winds, internal gravitational waves, tachocline mixing, or penetrative convection (e.g., Soderblom et al. 1990; Pallavicini et al. 1997; Jeffries 2014; Bouvier et al. 2018; Dumont et al. 2021b; Randich & Magrini 2021; Romano et al. 2021).

Even though a large amount of theoretical and observational work has been dedicated to the understanding of Li and its evolution, the complex pattern of Li depletion in PMS and MS stars is not yet well understood, preventing a more precise and quantitative use of Li as an age tracer (e.g., Sestito & Randich 2005; Randich & Magrini 2021). The most precise way to characterize the dependence of Li on these stellar parameters and derive a reliable Li-age relation is to conduct a comprehensive study of stellar groups with similar ages, such as OCs, associations, and

⋆ Based on observations collected with ESO telescopes at the La Silla Paranal Observatory in Chile, for the *Gaia*-ESO Large Public Spectroscopic Survey (188.B-3002, 193.B-0936).

This third and final paper encompassing the analyses and results from the PhD project (currently in revision to be published in A&A) will include the study of the dependence of the Li content of the cluster members with the aforementioned parameters, and conclude with the set of calibrated empirical Li envelopes which will be automated and fully exploited in our future work.

Thank you for your attention!



Full thesis available here:
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