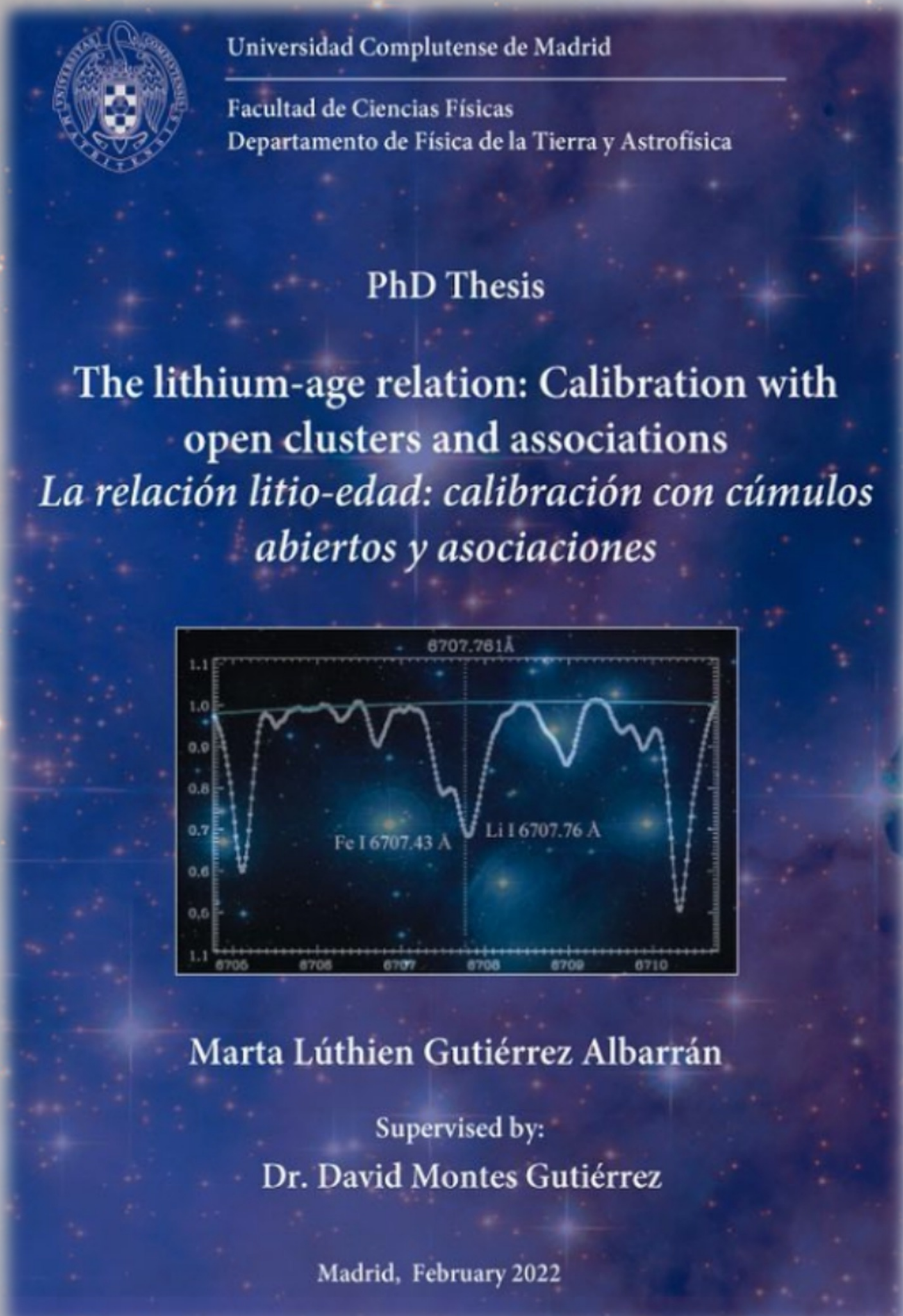

Universidad Complutense de Madrid

Facultad de Ciencias Físicas
Departamento de Física de la Tierra y Astrofísica

PhD Thesis

The lithium-age relation: Calibration with open clusters and associations

La relación litio-edad: calibración con cúmulos abiertos y asociaciones

Marta Lúthien Gutiérrez Albarrán

Supervised by:
Dr. David Montes Gutiérrez

Madrid, February 2022

Facultad de CC. Físicas
Universidad Complutense de Madrid

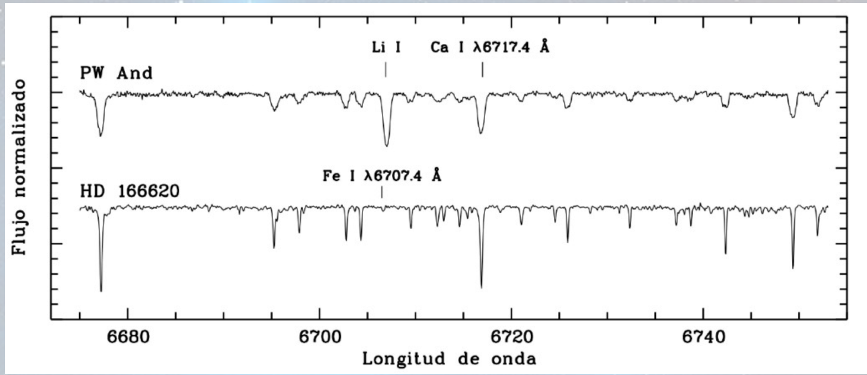
La relación Li-edad

Marta Lúthien Gutiérrez Albarrán

X Jornadas de Introducción a la Investigación 2022

Introduction: Lithium as an age calibrator

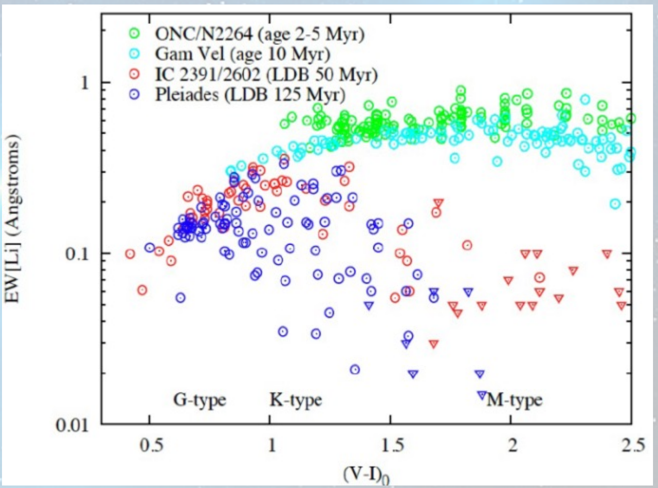
- ❖ Lithium (Li I spectral line at 6708 Å) is a **very sensitive indicator of youth in late-type FGKM stars and a useful tracer of stellar evolution.**



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**.

- ❖ 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).

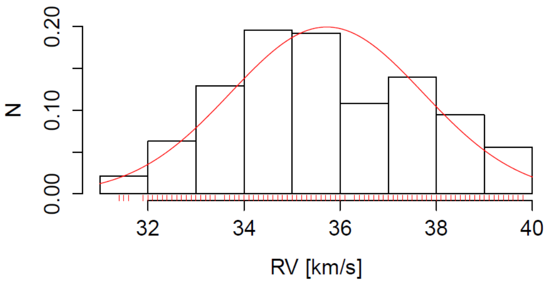
Data: Cluster sample

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

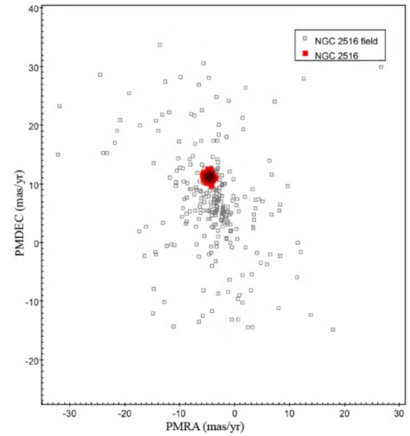
Cluster name	Age (Myr)	E(B-V)[a] (dex)	Distance (kpc)
NGC 6530	1–2	0.44 ± 0.10	1.33
ρ Oph	1–3	0.76 ± 0.13	0.13 ± 0.01
Trumpler 14	1–3	0.61 ± 0.10	2.90
Cha I	2	0.18 ± 0.08	0.16 ± 0.02
NGC 2244	4	0.49 ± 0.09	1.59
NGC 2264	4	0.05 ± 0.05	0.76
λ Ori	6	0.09 ± 0.04	0.41
Col 197	13	0.64 ± 0.07	0.80–0.90
γ Vel	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

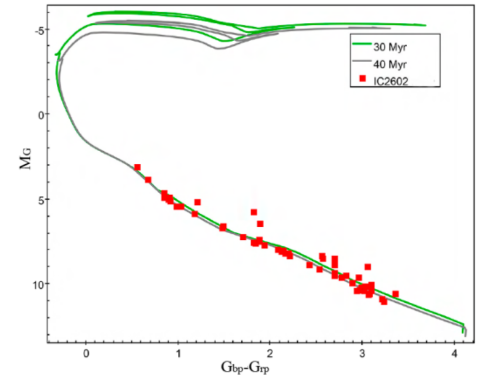
1) Membership analysis to obtain lists of robust cluster candidates



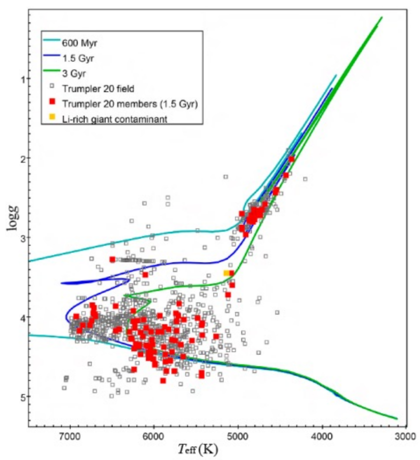
1) Analysis of *RV* distributions

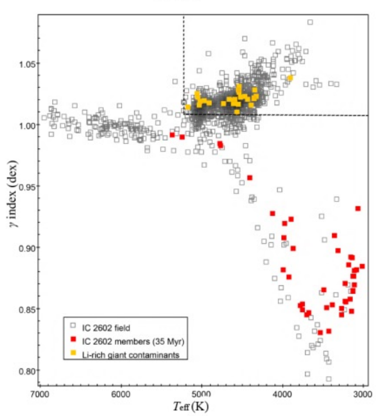


2) *Gaia* astrometry: proper motions and parallax

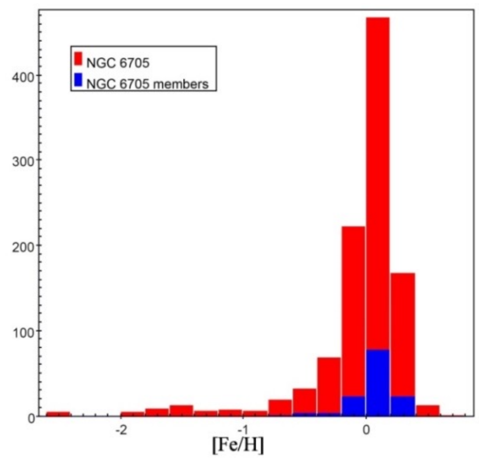


3) *Gaia* photometry (CMDs)

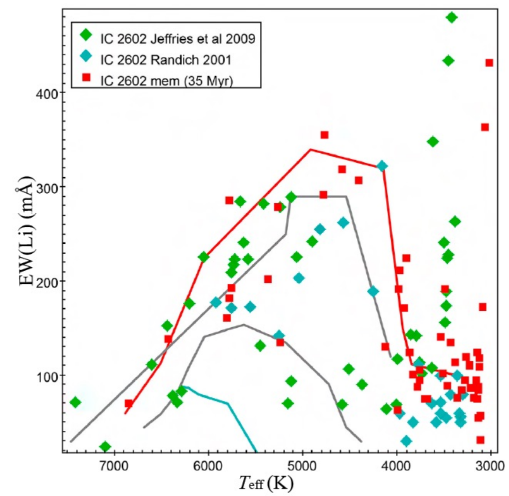




4) Gravity indicators: Kiel diagram and (γ, $T_{\rm eff}$) plane



5) [Fe/H] metallicity

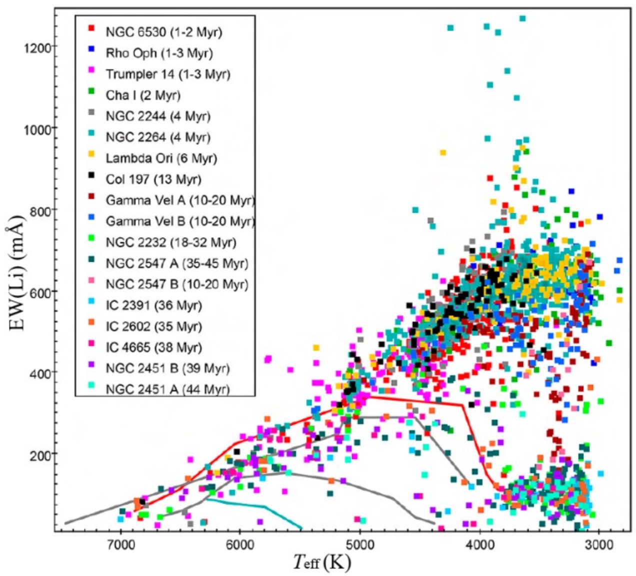


6) Position in *EW*(Li) vs $T_{\rm eff}$ diagram with **empirical envelopes as guide.**

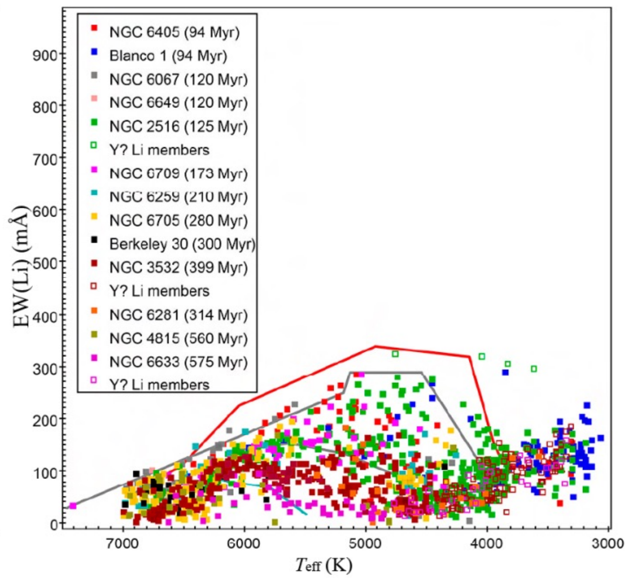
7) *Gaia* DR1, DR2 and EDR3 studies

Final member selections for all target clusters

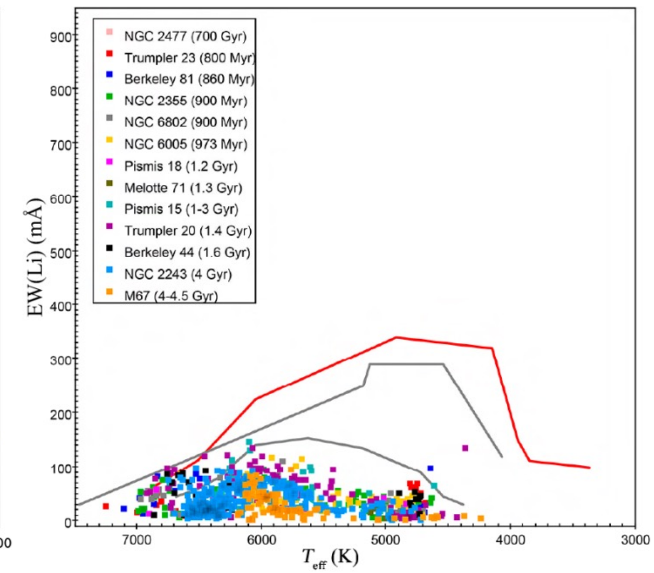
Young clusters (1-50 Myr)



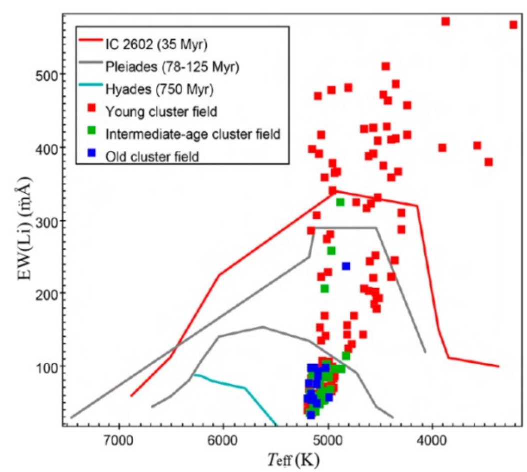
Intermediate–age clusters (50-700 Myr)



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: Publication in refereed paper

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

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)

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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_{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**

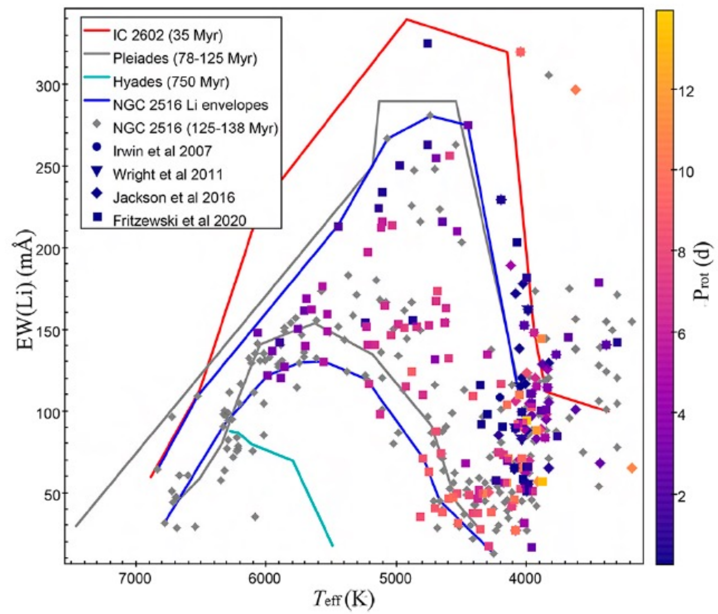
2) Dependence of Li with parameters

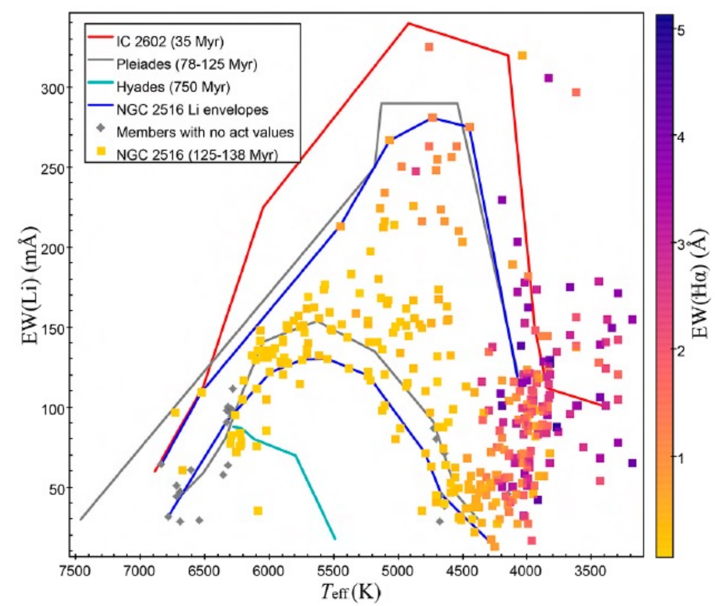
- **Influence of <u>rotation, activity, accretion</u>** and **<u>metallicity</u>** in the **observable lithium dispersion of the cluster candidates.**

- **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 → We systematically observed that **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**.

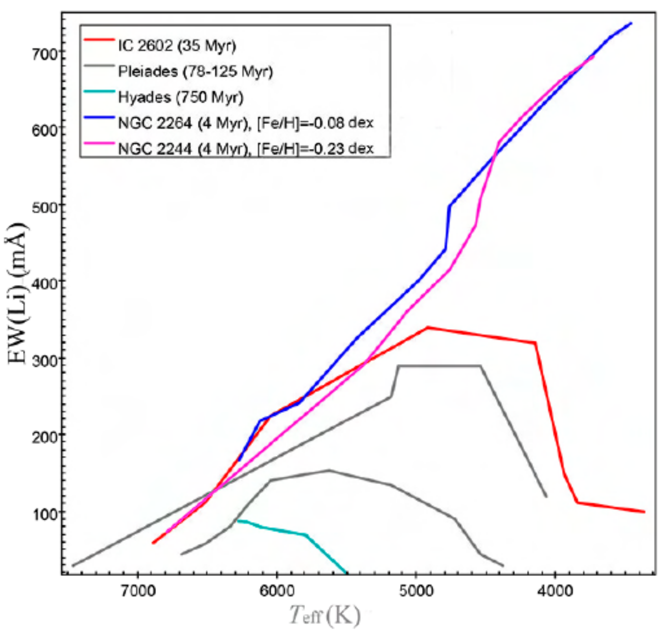


Figure 3.26: EW(Li)-versus-$T_{\rm eff}$ diagram comparing the upper Li envelopes for NGC 2244 (4 Myr, [Fe/H]=−0.23 dex) and NGC 2264 (4 Myr, [Fe/H]=−0.08 dex).

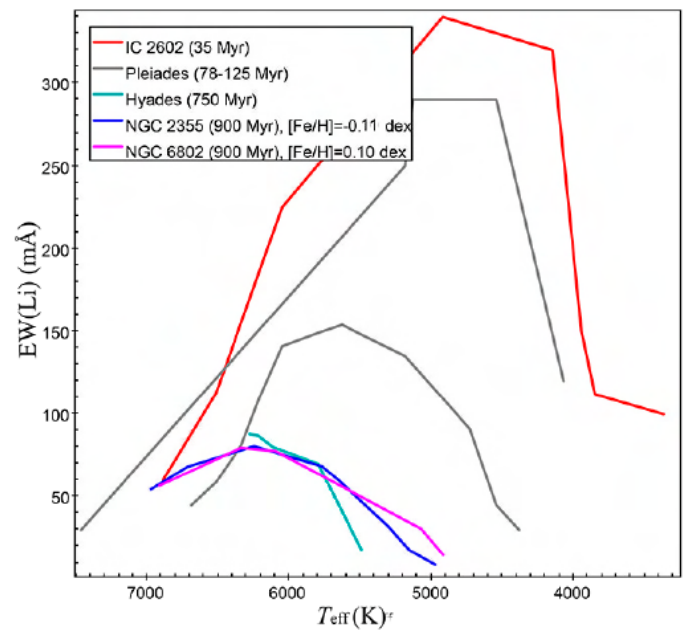


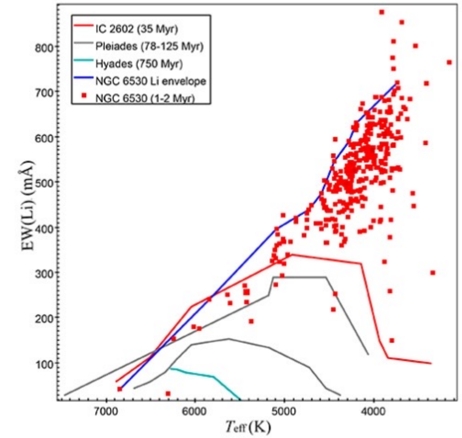
Figure 3.29: EW(Li)-versus-$T_{\rm eff}$ diagram comparing the upper Li envelopes for NGC 2355 (900 Myr, [Fe/H]=−0.11 dex) and NGC 6802 (900 Myr, [Fe/H]=0.10 dex).

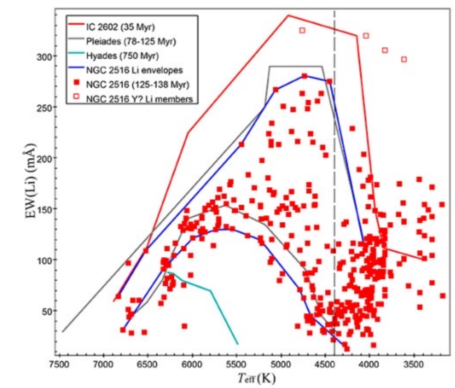
3) Calibration of the Li-age relation: Empirical Li envelopes

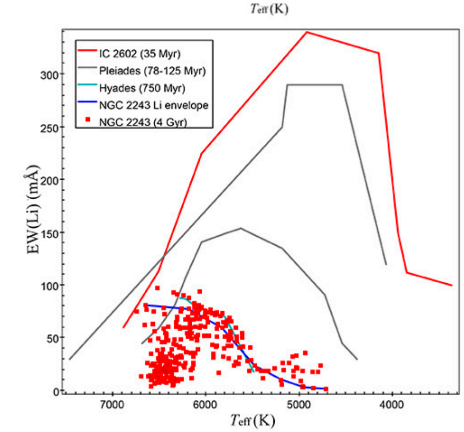
- **Empirical Li envelopes for key ages from 1–3 Myr to 4–4.5 Gyr,** tracing the **upper and/or lower limit of *EW*(Li) for a given T_{eff}** and **delimiting the regions populated by the cluster candidates** *(see examples for NGC 6530 (1-2 Myr), NGC 2516 (125-138 Myr), and NGC 2243 (4 Gyr), right)*

- **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 *(see IC 2602, below)*, **delimiting the LDB region** to better constrain the obtained Li envelopes.







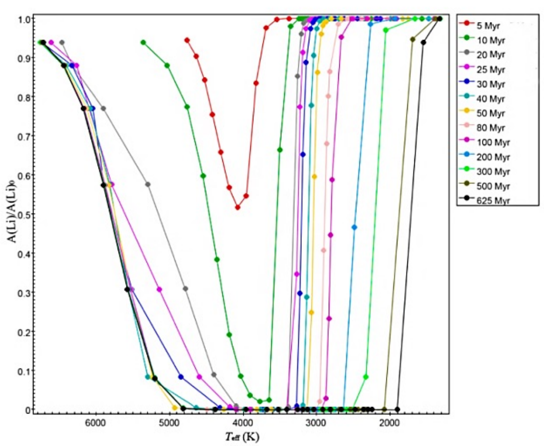
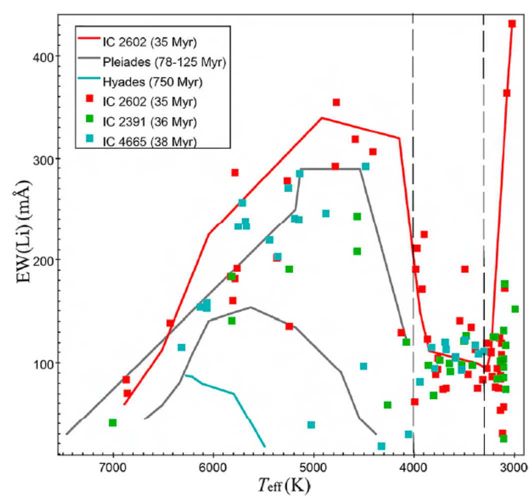
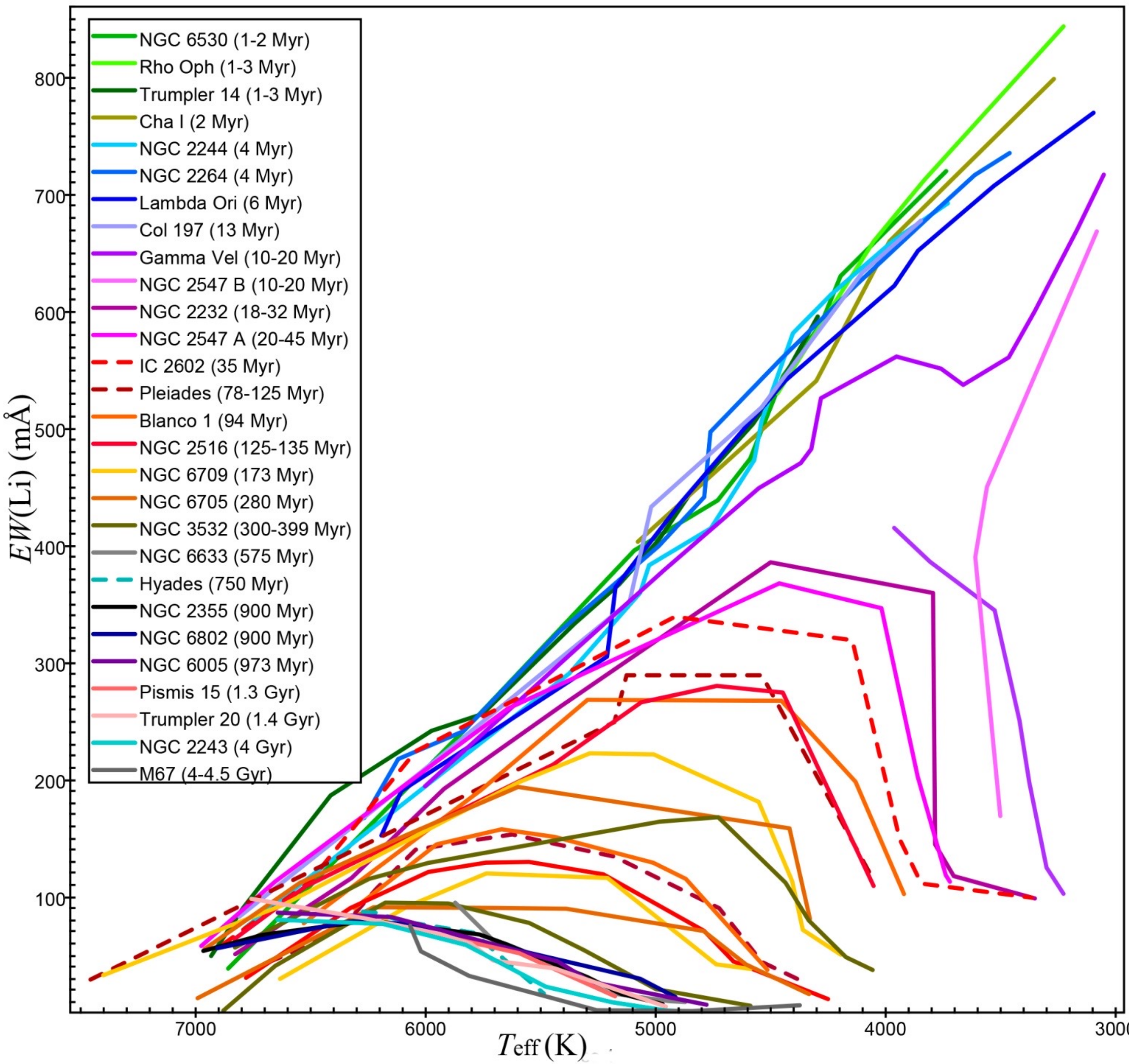


Figure 4.8: Evolutionary tracks from Baraffe et al. (2015) for an age range of 5–625 Myr, where $A(Li)/A(Li)_0$ is the ratio of surface Li abundance to initial abundance.



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**.

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


Thank you for your attention!