The evolution of lithium in FGK dwarf stars

The lithium-rotation connection and the Li desert

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ABSTRACT

We investigate two topics regarding solar mass FGK-type stars, the lithium-rotation connection (LRC), and the existence of the ‘lithium desert’. We determine the minimum critical rotation velocity (v\sin i), related with the LRC separating slow from rapid stellar rotators, to be 5 km s\(^{-1}\). This value also splits different stellar properties. For the first time we explore the behaviour of the LRC for some stellar associations with ages between 45 Myr and 120 Myr. This allows us to study the LRC age dependence at the beginning of the general spin-down stage for low-mass stars, which starts at \(\sim 30\)–40 Myr. We find that each stellar group presents a characteristic minimum lithium depletion connected to a specific high rotation velocity and that this minimum changes with age. For instance, the minimum changes from \(\sim 50\) km s\(^{-1}\) to less than 20 km s\(^{-1}\) in 200 Myr. This desert was described as a limited region in the A(Li)-T\(_{\text{eff}}\) map containing no stars. Using T\(_{\text{eff}}\) from Gaia DR2 we detect 30 stars inside and/or near the same box originally defined as the lithium desert. Due to their intrinsic T\(_{\text{eff}}\) errors some of these stars may be inside or outside the box, implying to a high probability that the box contains several stars. This leads us to consider that the lithium desert appears to be more a statistical distribution fluctuation than a real problem. We conclude that the lithium desert is rather due to a statistical distribution fluctuation than a real physical problem.

Key words. stars: rotation – stars: solar-type – stars: abundances

1. Introduction

When the presence of the fragile atom of lithium (Li) was correctly detected and measured for the first time in the Sun by Müller et al. (1975), a very important step was made towards understanding the stellar evolution of this element, the \(^7\)Li isotope. This evolution reflects the history of the destruction of the original lithium in which stars were born from the interstellar matter. The Li abundance, A(Li), of the interstellar medium depends on metallicity (Lambert & Reddy 2004; Lyubimkov 2016; Guiglion et al. 2019). In view of this, we adopted the value of A(Li) = 3.26±0.1, which is also compatible with the meteoritic value of A(Li) = 3.26±0.05 (Asplund et al. 2009).

Stars, especially FGK-types with near solar masses, which are our focus in this work, show two different stages of the Li depletion in their atmospheres. The first stage happens during the rapid pre-main sequence (PMS) phase, in which a circumstellar disk is magnetically connected to the stellar surface, producing a halt in the stellar rotation. Because of this, a rapid initial Li depletion occurs in an internal region between the base of the external convective zone (CZ) and the radiative stellar core. Here an important mixing is installed (see e.g., the model of Eggenberger et al. 2012).

Chavero et al. (2019) applied this model to solar mass FGK-type stars, finding that with an initial original A(Li) of \(\sim 3.2\) depleted values were obtained of the order of A(Li) \(\sim 2.0\) on a time scale of \(\sim 9\) Gyr, which is the lifetime of the protoplanetary disks before stars enter into the main sequence (MS) stage. During this last evolutionary phase, with a long lifetime scale of the order of 9–10 Gyr, a very slow and not well known physical Li depletion mechanism enters into action (see e.g., Dumont et al. 2021). This slow depletion action was first proposed by Herbig (1966). Nevertheless, rapid stellar rotations can interfere with the Li depletion process. This is especially the case of the younger stellar groups where rapid rotators are present. An important difference then appears, in which slow rotators are Li-poor and rapid rotators are Li-rich.

This property, which is part of the present study, is known in the literature as the lithium-rotation connection (LRC). Since the seminal study of this effect in the Sun by Conti (1968), the LRC mechanism has been the subject of several works. Contrary to some ideas that a rapid stellar rotator will induce a strong internal mixing that destroys Li, works by Butler et al. (1987) in the Pleiades open cluster (OC) with an age of \(\sim 125\) Myr and by Balachandran et al. (1988) in Alpha Per (50–70 Myr) showed that the largest rotations preserve Li. Soderblom et al. (1993) performed an extended research of the LRC in the Pleiades,
which was revisited by King et al. (2000) and earlier by Barrado et al. (2016) and Bouvier et al. (2018).

These works confirmed and amplified the results of Soderblom et al. (1993). Another recent work by Arancibia-Silva et al. (2020) found that LRC is also present in a different type of stellar group, such as the stellar stream Pec-Eri, with a similar age to the Pleiades. In this context a recent important analysis in the OC M35 (∼150 Myr) has recently been presented by Jeffries et al. (2020). Is the LRC a universal property in the sense that it is present at different ages and in different kinds of stellar groups? The LRC is present, for example, in NGC 2264, a very young OC with an age of 5 Myr (Bouvier et al. 2016), and it continues to be present up to ages similar to that of the Pleiades. A recent work has found indications of the presence of the LRC in an even younger OC (τ Ori) with an age of 3 Myr (Garcia Villota 2021).

We note that the LCR is also observed in different stellar young moving groups or associations (da Silva et al. 2009; Messina et al. 2016). Several theoretical mechanisms have been proposed to explain the LRC property. In general, these mechanisms involve the interaction between the base of the CZ and the hot internal burning region where Li is destroyed. These studies regard a very slow diffusion acting in this intermediate zone (Rüdiger & Pipin 2001; Tschäpe & Rüdiger 2001). Other works are related to the action of penetrative convective plumes (Siess & Livio 1997; Baraffe et al. 2017). Different mechanisms have also been invoked consisting of the reduction in temperature at the base of the CZ produced by atmospheric inflation processes (Somers & Pinsonneault 2014; Somers & Stassun 2017). For a recent complete review of the action of the LRC, see Bouvier (2020).

In the present study we first determine observationally the presence of a critical minimal velocity separating slow and rapid rotators, as is discussed in Baraffe et al. (2017). Another aspect that we consider here consists in studying the LRC behaviour in stellar associations just after the beginning of the general spin-down process era for solar mass stars, which happens at 30–40 Myr (see e.g., Bouvier et al. 2014). For this, we consider three stellar moving group candidates with a similar age of ∼45 Myr: the Tucana-Horologium association (THA), the Columba association (COA), and the Carina association (CAA; da Silva et al. 2009). We then consider the AB Doradus association (ABDA) with an age of ∼120 Myr with an age similar to that of the Pleiades OC (Bell et al. 2015; Bouvier et al. 2018).

Separately from the research within the present work described above, we also tackle another research, which refers to the existence (or not) of what is called the ‘lithium desert’ (Ramírez et al. 2012; Aguilera-Gómez et al. 2018). This consists of a peculiar zone placed in the general A(Li) versus effective temperatures \( T_{\text{eff}} \) map, in which apparently no stars are found.

Our work is based on a sample of 1307 field MS stars of spectral types F5 to K4, where 244 stars contain known planets and 1063 stars, a priori, without planets. We also consider 265 and 155 stars belonging to 14 OC and 4 associations, respectively. We have measurements of the Li abundances for all the mentioned objects with data obtained in the literature.

The stars chosen in this work are known as non-Li-Be-B dip stars, whose mechanisms of depletion, especially for Li, are related to the shallow convection layers of these early to mid-F-type stars acting in the above-mentioned temperature interval (see e.g., the model of Stephens et al. 1997). By avoiding these early to mid-F-type stars, we then consider, in general, stellar FGK objects with relatively low masses and relative large convective layers appropriate for a deep Li depletion acting mechanism, with stellar masses lower than 1.5 \( M_\odot \) (Pinheiro et al. 2014).

This work is the second in a series devoted to the study of Li, which started with Chavero et al. (2019). This paper is organised as follows. Section 2 presents the stellar data. Section 3 focuses on the study of the LRC. In Sect. 4 we address the problem of the existence or not of the lithium desert. Finally, we discuss and comment on the conclusions in Sect. 5.

2. Data collection

2.1. Sample of field stars

The origin of our current sample of field stars, listed in Table 1, is our previous work, Chavero et al. (2019). From this first set we increased the number of objects in the sample looking for stars with Li measurements taken with a similar methodology, all of which come from internally consistent ones measurements. The search was carried out by means of the Spanish Virtual Observatory (SVO) tool called VOMultiCatalog Interface.

It looks for the demanded stellar data by scanning all the catalogues within VizieR. In the case of lithium abundance, A(Li), we get information from about 11 catalogues (all references are displayed in Table 1). Once the stars have been identified, we proceed to triage them, as explained later.

In order to avoid any bias, we selected our stars without regard to their age, metallicity, rotational velocity or any previous detection (either dust nor planets). Just to detect if there is any influence by the presence of planets, in this work we take into account stars containing planets and those for which no planets have been detected. We proceeded this way since several studies presented evidence that the planetary formation process can modify the lithium of the host star (Israelian et al. 2004; Takeda & Kawanomoto 2005; Gonzalez et al. 2010). The nature of this disk-planet interaction will be object of study in another article.

A restrictive criterion that was imposed for the selection of the stars in the sample was, in addition to known A(Li), that the spectral types were FGK-type stars and whose masses were \( M_\star < 1.5 \, M_\odot \). We thus eliminated, from the first sample, giant and subgiant stars. We found more than 2000 stars with reliable A(Li) values, but we dismissed this number of stars because we introduced a cut off in age at 10.5 Gyr. This cut is in order to eliminate the most evolved stars.

The final sample of Li abundances includes stars from the next 11 catalogues: Chavero et al. (2019) as well as Aguilera-Gómez et al. (2018), Bensby & Lind (2018), Cutispoto et al. (2002), Delgado Mena et al. (2014), da Silva et al. (2009), Gezzi et al. (2010), Gonzalez (2015), Luck (2017), Ramírez et al. (2012), Thévenin (1998). These works were selected because their data are coming from internally consistent measurements. We solved the dilemma of finding values from different authors by prioritising those from the most recent publication. In the case of being our measured values from Chavero et al. (2019) these were chosen in any case. For the corresponding stellar physical parameters, described below, we sought the greatest homogeneity among the different sources from which the data were collected.

The values of \( T_{\text{eff}} \), without any restriction or cut both upper and lower, and parallaxes, were obtained from the Gaia DR2 catalogue (Gaia Collaboration 2016, 2018). It gives uncertainty values for the effective temperature in terms of lower \( (b_{T_{\text{eff}}}) \)
and upper limits ($B_{\text{T}_{\text{eff}}}$), terms in which $T_{\text{eff}}$ values appear in the Gaia DR2 catalogue. All our stars belong to the “clean” subsample of $T_{\text{eff}}$ recommended by Andrae et al. (2018). We obtained the values of [Fe/H] from Gáspár et al. (2016) and Soubiran & Militzer (2016). V magnitude values were collected from the SIMBAD database. The search of $v \sin i$ implied searching within 30 catalogues. In this case we established as a priority the values published by Brewer et al. (2016), and Delgado Mena et al. (2015). In the case of not finding this value in the most recent works, we took them from the catalogue of Glebocki & Gnacinski (2005). All the catalogues from which the data have been obtained are listed in Table 1, along their respective references.

The age values have been obtained from 29 catalogues (see Table 1), in such a case we prioritised the more recent values, usually Delgado Mena et al. (2019). However, this age scale might introduce inhomogeneities. Thus, for achieving greater homogeneity and for consistency with our previous work, we chose to derive ages and other evolutionary parameters, such as masses and radii, by using the PARAM 1.3 code (da Silva et al. 2006). This code requires $T_{\text{eff}}$, [Fe/H], $V$ magnitude and parallax. So we have two sources for the age and the mass: one that comes from the literature, as described above, and the other from this work using PARAM3.

As mentioned in the introduction, this work is part of a set of them dedicated to the study of Li, which led us to complete the physical characteristics of our sample with the values of chromospheric activity index, $log R^\prime_{HK}$, which were mainly collected from Boro Saikia et al. (2018). When we did not find values in this catalogue we looked for them in Krejčová & Budaj (2012). In the first case, there are compiled 4454 stars, whose chromospheric activity was collected from a set of different sources. Such catalogue served to study the behaviour of the variation in the chromospheric activity of cool stars along the MS. The catalogue of Boro Saikia et al. (2018) listed different values for some stars. In such a case, we catalogued the average value and, as the error, the difference between the maximum and the minimum value. Also, using Gaia DR2 parallaxes, proper motions and radial velocities, and using the public software package Pygaia4, we obtained the galactocentric velocities $U, V, W$ for all stars in our main catalogue. These last kinematic parameters plus the chromospheric activity are included in the sample to be used in a parallel work.

An additional observation is that, even within the giant planet regime, binaries tighter than 100 au show a different distribution of masses, suggesting a different formation mechanism and/or dynamical history (Duchêne 2010). In view of all these studies, we excluded from our samples 96 binary systems with different formation mechanism and/or dynamical history (Duchêne 2010). In view of all these studies, we excluded from our samples 96 binary systems with different formation mechanism and/or dynamical history (Duchêne 2010). In view of all these studies, we excluded from our samples 96 binary systems with different formation mechanism and/or dynamical history (Duchêne 2010). In view of all these studies, we excluded from our samples 96 binary systems with different formation mechanism and/or dynamical history (Duchêne 2010). In view of all these studies, we excluded from our samples 96 binary systems with different formation mechanism and/or dynamical history (Duchêne 2010). In view of all these studies, we excluded from our samples 96 binary systems with different formation mechanism and/or dynamical history (Duchêne 2010). In view of all these studies, we excluded from our samples 96 binary systems with different formation mechanism and/or dynamical history (Duchêne 2010). In view of all these studies, we excluded from our samples 96 binary systems with different formation mechanism and/or dynamical history (Duchêne 2010). In view of all these studies, we excluded from our samples 96 binary systems with different formation mechanism and/or dynamical history (Duchêne 2010).

Next are the relations between $Li, [\text{Fe/H}], T_{\text{eff}}$, and the age of this work (TW) with respect to AG18 listed values:

$$A(Li)_{\text{TW}} = 0.99A(Li)_{\text{AG18}} + 0.01, R^2 = 0.99,$$

$$[\text{Fe/H}]_{\text{TW}} = 0.99[\text{Fe/H}]_{\text{AG18}} + 0.001, R^2 = 0.99,$$

$$T_{\text{eff}}\text{TW} = 0.93T_{\text{eff}}\text{AG18} + 397, R^2 = 0.88,$$

$$Aget\text{TW} = 0.88Aget\text{AG18} + 0.33, R^2 = 0.81.$$

The relations are similar. The main difference is in the number of stars with $v \sin i$ known: stars with planets 115 (AG18 sample) against 245 (our sample), stars without planets 358 (AG18 sample) against 931 (our sample). The two samples, AG18 and ours, show the same statistical distribution of the lithium abundance, even grouping into stars with and without planets and the total sample size (see Fig. 1).
Table 1. Stellar parameters of the sample.

| Star          | SpType | T eff (K) | M sin (M⊙) | [Fe/H] | A(Li) | v sin i (km s⁻¹) | Age (Gyr) | Age(Li) | log R sin² | U/V/W | Pl |
|---------------|--------|-----------|-------------|--------|-------|-----------------|------------|---------|------------|--------|----|
| HD1461 G5V    | 5764 ± 81 | 1.06 ± 0.03 | 0.19 ± 0.01(46) | 0.6 ± 0.07(25) | 1.8(1) | 3.1 ± 2.3 | 5.6 ± 1.5(71) | −5.14 ± 0.18(30) | −31.74, −38.86, −1.62 | Y    |
| HD1832 G2/3V  | 5773 ± 74  | 0.98 ± 0.03 | −0.03 ± 0.03(46) | 1.08 ± 0.07(25) | 2.8 ± 0.5(71) | 3.1 ± 2.3 | 5.6 ± 1.5(71) | −4.64 ± 0.15(30) | −7.27, −62.72, −16.94 | N    |

Notes. (1) Column 1: Henry-Draper catalogue name; Col. 2: spectral type; Col. 3: effective temperature taken from Guía DR2 where the uncertainty is taken as (b, T eff = b, T eff) / 2; Col. 4 stellar mass calculated using PARAM code; Col. 5: stellar metallicity; Col. 6: lithium abundance; Col.7: projected rotational velocity; Col. 8: stellar age calculated using PARAM code; Col. 9: stellar age taken from literature; Col. 10: chromospheric activity index; Col. 11: presence of planet Yes or No; Col. 12: galactocentric velocities U, V, W. The full table and references are only available at the CDS.

References. (a) Gáspár et al. (2016); (A) Chavero et al. (2019); (B) Aguilera-Gómez et al. (2018); (1) Brewer et al. (2016), (2) Marsden et al. (2014); (3) Aguilera-Gómez et al. (2018); (4) Boro Saikia et al. (2018).

2.2. Sample of open cluster stars

To be able to have more references in terms of stars with high rotation speeds, we include stars of open clusters with an abundance of known Li that also allows us to have a larger sample of stars younger than 300 Myr. The aim is to establish a reference (Table 2) constructed with the cluster data that, in addition to the stellar sample (Table 1), helps us to explain our results. The first source of data comes from the stars with Li abundances identified in the literature and belonging to open clusters, collected by Sestito & Randich (2005) and published in WEBDA. We added data of the OCs NGC 6253 (Cummings et al. 2012) and NGC 3680 (Anthony-Twarog et al. 2009) in order to increase the age range of cluster stars within the same range of T eff and surface gravity (log g) (i.e., MS stars). The ages were taken mainly from Kharchenko et al. (2013).

In the present study we assume uniform Li abundance in a cluster before any Li depletion occurs. However, to zeroth order, the initial Li of near-solar metallicity open clusters should be similar to the meteoritic abundance. This A(Li) value is observed in very young open clusters, which are generally in the range of A(Li) = 3.0 to 3.4. We assumed that for the normal stars of the youngest cluster NGC 2264, many T Tauri stars do not present Li depletion.

Table 2 contains data of the OCs and the young stellar associations that are considered in this work. We performed a deep probabilistic study to ensure that each cluster star is a member of its host cluster. The membership is based upon the probability of following and applying the criteria quoted from Kharchenko et al. (2013) and Dias et al. (2014a,b), such that a star is a member of its host cluster if its probability of belonging to it is around 61% in the Dias catalogue, and stars with kinematic and photometric membership probabilities higher than 60% in the Karchenko catalogue. With these crossed restrictions, we admit confirm that our selected stars are members of their respective host clusters with a high probability, at least 90%.

We checked whether the cluster stars are MS stars by means of the colour-magnitude diagram (CMD) of every cluster. We conclude and confirm from all these CMDs that all our sample cluster stars belong to the MS with 4000 K < T eff < 6500 K. The stellar parameters of cluster stars, such as effective temperature, T eff; projected rotational velocity, v sin i; stellar mass, M sin, and metallicities, [Fe/H], were collected from the literature. Exceptionally, when a T eff value was not found we quoted the one listed in WEBDA. The literature values are collected by means of VOMultiCatalog-Interface. The sample of cluster stars

5 The WEBDA database is operated at the Department of Theoretical Physics and Astrophysics of Masaryk University.

Table 2. Parameters of stars in open clusters and stellar associations.

| Cluster | Star          | v sin i (km s⁻¹) | A(Li) | T eff (K) | Age (Gyr) | References |
|---------|---------------|-----------------|-------|-----------|------------|------------|
| IC 2602 | IC 2602 120   | 51.2            | 3.19  | 5650      | 0.037      | a,b        |
| IC 2602 | IC 2602 131   | 45.7            | 3.06  | 6147      | 0.037      | a,b        |
| IC 2602 | IC 2602 112   | 14.7            | 2.98  | 6041      | 0.037      | a,b        |
| IC 2602 | IC 2602 157   | 11.8            | 2.92  | 5624      | 0.037      | a,b        |
| IC 2602 | IC 2602 2290  | 19.2            | 1.76  | 4553      | 0.037      | a,b        |
| IC 2602 | IC 2602 2830  | 30.0            | 3.22  | 5746      | 0.037      | a,b        |
| IC 2602 | IC 2602 2951  | 10.9            | 3.00  | 5190      | 0.037      | a,b        |

References. (a) WEBDA, (b) Sestito & Randich (2005), (c) Stauffer et al. (1997). Full version of the table and references are only available at the CDS.

and their parameters is large enough to explore how the lithium abundance, A(Li), behaves in stars belonging to OCs.

The total number of remaining OC stars being part of this study is 265 objects. Their spectral types are mainly F-, G-, and K-type stars. Although the listed values of A(Li) were computed assuming local thermodynamic equilibrium (LTE) and non-local thermodynamic equilibrium (NLTE), our study is based in general on the NLTE assumption. All the cluster and star data are listed in Table 2, which contains, for each OC and association the identification, age in Gyr, star name, v sin i in km s⁻¹, Li abundance, and effective temperature T eff in K.

2.3. Sample of young stellar associations

We consider four stellar associations and studied for the first time the LRC process (see Table 2) in stars with stellar effective temperature T eff > 4000 K. These are three moving groups with a similar age of ~45 Myr, the Tucana-Horologium, Columba, and Carina associations, and a fourth one, the AB Doradus association with an age of ~120 Myr (da Silva et al. 2009). Thus, the sample (field stars and OC stars) is widened by the addition of 167 stars of young stellar associations.

We also compare this last group to the OC Pleiades (125 Myr) because these two stellar groups are considered to have a common origin (Luhman et al. 2005; Ortega et al. 2007), and they also have a similar age. These studies permit us to see the evolution of the LRC first in an age interval of near 100 Myr.

This study requires a careful examination of which of the published members of these associations are to be considered intruder members. In principle, there are two methods for detecting them: by means of galactic dynamics or by chemical abundance analysis. In the dynamical method the 3D orbits of all
the members of a moving group follow dynamical trajectories from an initial point considered to be the origin of the association in the past, up to the present observed positions. These orbits are established by the action of a simplified Milky Way gravitational potential. Any interloper is easily detected because its orbit would follow a very different trajectory from all the members of the group. In the dynamical method used by Ortega et al. (2007), used to determine the origin of ABDA from the Pleiades, any interloper members have been detected. Nevertheless, a chemical analysis by Barenfeld et al. (2013) of ABDA suggested that some members of what they call the stream, in contrast to the nucleus of ABDA, contain certain suspicious chemical members. In any case, the metallicity determined by Ortega et al. (2007) is compatible with that obtained by Barenfeld et al. (2013).

Translated into an intruder selection, we identified as a non-member any star that has a specific individual metallicity value different by more than a factor 0.1 dex from the mean metallicity of each of the group. For this we first estimate the mean metallicity ([Fe/H]) of each association by considering the ensemble of members presenting a homogeneous distribution of metallicities. We are aware that these are new values in the sense that we have not found comparable values in the literature, with the exception of ABDA. The respective mean metallicities are for THA [Fe/H] = −0.04, for COA [Fe/H] = 0.002, for CAA [Fe/H] = 0.02, and for ABDA [Fe/H] = 0.02. For ABDA we note that a more precise value for the metallicity obtained by Barenfeld et al. (2013) is equal to 0.02 ± 0.02. The respective intruders are not considered in this work, and we identify them in the figures with a black square in each of the A(Li) versus $v \sin i$ figures presented and also marked in Table 2.

3. The lithium-rotation connection

As mentioned in the Introduction, stellar rotation plays a very important role in Li depletion during the PMS and MS evolutionary stages. When the projected rotational velocity is such that $v \sin i > v_{cr}$, where $v_{cr}$ is a critical rotation velocity the stars inhibit somehow the Li depletion, and they appear as Li-rich stars. Determining its critical value is the objective of this work. On the contrary, if the $v \sin i < v_{cr}$ (i.e. below 5 km s$^{-1}$) the stars appear as Li-poor stars. This is the case for the FGK-type stars with masses between 0.8–1.4 $M_{\odot}$ considered in this work. There are very few exceptions, which will be discussed below. This property represents the LRC as defined in the Introduction. In Sects. 2.2 and 2.3 we discuss the contents of our data concerning the stellar open clusters and associations, respectively.

Here we discuss some of the main properties of field stars, which represent a large part of our data. For this we present in Fig. 2 a general map of the distribution of the Li abundances A(Li) of field stars (being planet hosts or not) as a function of $T_{\text{eff}}$, Gaia velocities. In addition, a scale of their $v \sin i$ velocities is introduced in the figure. The aim of Fig. 2 is to show the three parameters involved together, $T_{\text{eff}}$, $v \sin i$, and A(Li) and to explore some indications of the presence of a global LRC effect and also of a $v \sin i$ critical value separating rapid and slow stellar rotators. As can be seen, this figure is dominated by the presence of slow rotators (red points) which could be of different ages. Some medium and rapid stellar rotators (yellow and blue points) at high $T_{\text{eff}}$ values are also present, which suggest the presence of a weak LRC effect. However, due to the complete mixture of ages among these field stars, and the presence of several slow rotators stars in the Li-rich region, no robust conclusion can be obtained. This is also the case with the determination of any critical velocity, even in the presence of very few stars (yellow points) with $v \sin i > 5$ km s$^{-1}$. We conclude that the presence of the LRC and a critical $v \sin i$ must be studied using other methodology and this is the subject of the next sections.

Within Fig. 2 are stars that do not adhere to the general behaviour. They are identified by the following characteristics. There are four stars (HD 149724, HD 16548, HD 166, and HD 211080) with $T_{\text{eff}} < 5700$ K and low rotation ($v \sin i < 5$ km s$^{-1}$), but high abundance (A(Li) > 2.0). Their high abundance is explained by their high metallicity (average of [Fe/H] = 0.22) and high activity (average of log $K_{\text{HK}}$ = −4.54 face to the mean value of −4.75), as described in Boro Saikia et al. (2018).

Additionally, in Fig. 2 there are six stars of late F-type with $T_{\text{eff}} > 5700$ K and high rotation ($v \sin i > 8$ km s$^{-1}$), but low abundance (A(Li) < 1.5); HD 107213, HD 185720, HD 201203, HD 30736, HD 53665, HD 86264. The action of rotationally induced slow mixing can explain the low Li value as the result of slow Li mixing in these stars that are currently undergoing angular momentum loss and are sufficiently massive (average $M_{\odot}$ ~ 1.4) that interior temperatures and densities are sufficiently high to burn Li as a result of such mixing (Baugh et al. 2013). More detailed conclusions on the critical velocity are discussed in Sect. 3.1. In addition, many more properties of the LRC obtained with the help of stars of clusters and associations are discussed in Sect. 3.2.

3.1. The minimum critical rotational velocity of our complete sample stars

In this section we set out to obtain a numerical figure that is the actual physical value for field stars and cluster stars. Figure 2 guides us to visualise a value for critical rotational velocity, separating fast and slow rotating stars. Figure 3 shows A(Li) as a function of the projected rotational velocity, $v \sin i$, colour-coding by the age and the effective temperature. We note that the ages estimated for field stars (see Table 1) are much less precise than those of cluster ages (Table 2). We do not represent the masses on the third axis since we only have the values of these for the field stars; in doing so with the $T_{\text{eff}}$, we
Fig. 3. $A$(Li) vs. $v\sin i$. Points are colour-coded according to the age (panels a, c, e) and $T_{eff}$ (panels b, d, f) of the stars (see the colour bars on the right). Panels a and b: field stars without detected planets; panels c and d: field stars with detected planets. Cluster stars are represented in panels e and f. The diagram of panel e shows the age in a logarithmic colour scale ranging from dark blue for 0.035 Gyr to red for 5 Gyr.
preserve homogeneity, while it is a way of representing the equivalent masses. In short, the identification of the critical rotational velocity involves the other involved stellar parameters.

Our search for this critical $v \sin i$ rotational velocity, also involves the investigation of the effects of the physical parameters mentioned above. Our method is based on analysing the mosaic depicted in Fig. 3. We first consider the case of the very slow rotational velocities with $v \sin i \leq 5$ km s$^{-1}$. In Fig. 3, for all the lithium abundances ranging from A(Li) $\sim 0.0$ to 3.3, the field and cluster stars present a mixed collection of ages and $T_{\text{eff}}$ values. This collection represents some different Li evolution scenarios. For field stars without planets (Figs. 3a, b) and with planets (Figs. 3c, d), we can distinguish two intervals of A(Li) bounded by the value of A(Li) $\sim 2.5$. In general, stars with A(Li) $< 2.5$ are cooler than $\sim 6000$ K and older than 4 Gyr. For the less numerous Li-rich stars with A(Li) $> 2.5$, these are younger than $\sim 3$ Gyr and hotter than 6000 K. We note that this behaviour is similar for stars hosting planets or not. In the case of clusters (Figs. 3e, f) the presence of very cool stars ($\sim 4500$ K) is more accentuated for A(Li) $< 2.5$. For Li-rich stars with A(Li) $> 2.5$, stars appear to have temperatures of 6000 K or higher, with ages between $\sim 0.2$ Gyr and 0.6 Gyr. We note that the separating value of the lithium abundance of 2.5, not only distinguishes two different zones of age and temperatures, as can see in Fig. 3, but is remarkably similar to the upper limit of the final PMS depleted Li values between 2.2 and 2.4, as found in Chavero et al. (2019).

We also examine the situation for higher rotational velocities ($v \sin i > 5$ km s$^{-1}$) for field stars, hosting planets or not, and for those belonging to clusters. First of all, stars with A(Li) $> 2.5$ present in all cases a normal behaviour for the LRC phenomena. This means, for high rotation velocities, that stars maintain in general their original lithium abundances. We note that cluster stars, differently from field stars, present very high rotational velocities, as expected because some of them are younger than those of our field sample. What appears to be more peculiar in this case of higher velocities is the presence of dispersed, relatively Li-poor stars with A(Li) $< 2.0$. This peculiarity is more apparent if we consider that the temperatures of dispersed field stars are opposite to those in clusters. Dispersed field stars are hot and cluster stars are cool. However, in both cases they are relatively young objects. This difference indicates different origins. In the following we try to explain these origins. We first consider the case of the OCs.

A complete discussion on this is given in the Sect. 3.2. Nevertheless, we can say that in OCs, which occupy a large range of ages, their stars undergo after 30−40 Myr a general spin-down effect (Bouvier et al. 2014). During this process, the cool K-type member stars are the first, in each cluster, to be Li depleted. In this way, from ages around 100 Myr and older, K-type dwarfs begin to successively move down to the low-Li abundance zone (see e.g., the case of the Pleiades OC with an age of 125 Myr in Fig. 5b). The presence of the dispersed cool stars and relative young stars in clusters in Figs. 3e, f is the result of this process.

The distribution of field stars as shown in Figs. 3a−d requires a different explanation from that of the OC because their evolution differs from what we call the general and standard Li depletion processes in solar-type stars. As mentioned before, the most important Li depletion occurs in the initial T Tauri phase. Here, around 70% of T Tauri stars (Armitage et al. 2003) maintain their accretion disks with lifetimes up to 10 Myr. In the Introduction we mentioned that using the accretion disk braking model of Eggenberger et al. (2012) the Li abundances are reduced to A(Li) values near 2.0 (Chavero et al. 2019).

In Figs. 3a−d two different zones appear to escape this standard Li depletion process. They are represented first by a few Li-rich objects, with low rotation velocities ($v \sin i \leq 5$ km s$^{-1}$). The second group is formed by dispersed Li-poor objects with higher velocities ($v \sin i > 5$ km s$^{-1}$). These stars are hotter than 6000 K and younger than 4 Gyr. In summary, these last-mentioned two groups present mechanisms inverse to those acting in the standard Li process. Even if these two groups represent minor groups, they require future, non-standard physical explanations, which consider supplementary mechanisms in the complex disk−star interaction (Ireland et al. 2021). We presented an ensemble of different stellar properties, such as age and temperature (or mass equivalent) for stars with rotational velocities lower or higher than $v \sin i = 5$ km s$^{-1}$. Considering all this physical evidence, we can conclude that the velocity of $v \sin i$ of 5 km s$^{-1}$ is the most representative critical rotational velocity to differentiate slow and rapid stellar rotators, and also stellar properties.

This determined critical value of $v \sin i$ is important in the light of models trying to explore the LRC mechanism. For instance, Baraffe et al. (2017) use a new diffusion mechanism by means of hydrodynamic simulations. They introduce an overshoot in the form of plumes at the lower edge of the CZ. Their results show that stellar rotation affects the mixing in the CZ bottom. One of their main results is the prediction of the existence of a critical rotation above which the rotation prevents the penetration of any plumes. In addition, below this critical velocity value, rotation has little or no effect, even in the case of the most vigorous plumes.

### 3.2. The complete pattern of the lithium-rotation connection

The representation of the variation in A(Li) as a function of rotational $v \sin i$ velocities for a stellar group (OC or association) is a very practical representation to distinguish changes in the behaviour of the Li depletion. The general pattern of the LRC is formed by two very different behaviours, on the one hand by the presence of stars with very low $v \sin i$ values ($\leq 5$ km s$^{-1}$) covering a wide range of the A(Li) depleted values, from the initial value of $\sim 3.3$ down to very depleted near zero values in some cases. It is generally considered that stars presenting this behaviour have braked their larger past rotations, for example by the PMS mechanism, as mentioned in the introduction (Eggenberger et al. 2012) and by a slow Li depletion mechanism during the MS. On the other hand, a completely different behaviour appears when the projected rotational is over the initial threshold velocity of $\sim 5$−10 km s$^{-1}$.

These stars appear to be less and less Li depleted. This pattern shows that the Li depletion is reduced progressively up to a minimum stage. As we discuss below, this specific minimum Li depletion changes with age. Let us reconsider and ask ourselves if the Li depletion for all large and very high rotational velocities continues to be constant or if it diminishes. Is this behaviour age dependent?

Figure 3b shows that there are some speeds above 5 km s$^{-1}$ at which the A(Li) reaches the primordial value to decrease for higher $v \sin i$ values. Not being able to know precisely what these critical speeds were, we decided to examine here the behaviour of the LRC action using young stellar moving groups or associations with different ages: the Tucana-Horlogium, the Columba, and the Carina associations with a similar age of 45 Myr (da Silva et al. 2009), and the AB Doradus association with an age of $\sim 120$ Myr (Bell et al. 2015). We also examined the Pleiades OC.
3.2.1. The Tucana-Horologium, Columba, and Carina associations

The stellar moving groups or associations THA, COA, and CAA are sparse groups of stars located at distances between 35 and 160 pc. Each association is distinguishable by the similar space velocities in all of its components. Each association is considered to have a specific spatial formation region in an interstellar cloud, now vanished. It is from this original place of formation that all members began to move. Determining the time elapsed since the considered epoch of formation and the time of the present observable positions is one of the methods used to obtain the age of the group. The discovery of THA was made by Torres et al. (2000) and Zuckerman & Webb (2000), whereas the discovery of COA and CAA were made and discussed by Torres et al. (2008). The source of A(Li) and \( v \sin i \) data to study the LRC for these three moving groups are from da Silva et al. (2009). In Fig. 4 we present the distribution of A(Li) as a function of \( v \sin i \) for the ensemble of these three associations having similar ages. The internal errors of the A(Li) values are discussed in da Silva et al. (2009) and are in general less than a factor 0.2. In any case, the internal errors will not modify in a significant way the general distribution of points in Fig. 4. The presented values of A(Li) and \( v \sin i \) are then sufficient to reach our goal. The rotational velocities \( v \sin i \) are projected velocities that do not always represent the true equatorial rotational velocities. Some considerations about these differences of velocities are discussed in Sect. 3.2.3.

The respective number of our detected intruder members in the lists of da Silva et al. (2009) of these three associations are THA (8 intruders), COA (3), and CAA (3). All these considered non-members are shown in Fig. 4 as black squares overlapping the different symbols corresponding to each association. We adopt here the ages of Bell et al. (2015). Using a self-consistent isochronal scale, they obtained the following ages for these three associations: THA (45 \( \pm \) 4 Myr), COA(42\(^{16}_{-9}\) Myr), and CAA(45\(^{11}_{-7}\) Myr). For our comparative analysis we consider a mean age equal to 45 Myr for all of them.

The distribution of points in Fig. 4 representing the real considered members of THA, COA, and CAA have the general typical pattern expected to reflect the LRC, as mentioned before. The LRC is represented by stars showing highly Li depleted stars for \( v \sin i < 10 \text{ km s}^{-1} \).

For larger \( v \sin i \) velocities, an important feature appears in Fig. 4. This is the presence of a minimum of the Li depletion corresponding to the rotational velocity of \( v \sin i \sim 50 \text{ km s}^{-1} \). For even larger velocities, FG-type stars are distributed in an almost horizontal sequence. Instead, K-type dwarf stars show a much more important Li depletion for very rapid stellar rotators. As we explain in the next subsection, older stellar groups present different behaviours regarding this general stellar distribution of the LRC.

### 3.2.2. The AB Doradus association

The most richly populated association, ABDA, is the most studied among the moving groups considered here. The literature gives a collection of different ages. They are presented in increasing age scale from 50–70 Myr (Zuckerman et al. 2004; Torres et al. 2008; da Silva et al. 2009) to a coeval age of 119 \( \pm \) 20 Myr in Ortega et al. (2007). The most recent age values for ABDA are those of Bell et al. (2015), who give an age of 149\(^{49}_{-51}\) Myr. In order to study in greater detail the common origin of ABDA and the Pleiades OC we compare the action of the LRC in the two stellar groups. Figure 5a shows the distribution of A(Li) in function of \( v \sin i \) velocities of stars of ABDA. Figure 5b presents the same distribution for stars in the Pleiades for which both values of the \( v \sin i \) projected rotation velocities and the A(Li) values are from Barrado et al. (2016). New features appear for these stellar structures that are almost 100 Myr older than the previous three younger associations considered. In ABDA the minimum Li depletion appears at \( v \sin i \sim 30 \text{ km s}^{-1} \), which is a lower value than that of \( \sim 50 \text{ km s}^{-1} \) of the 45 Myr associations. At this velocity, two branches of stars appear instead of one branch, as was the case of the younger associations.

As can be seen in Figs. 5a and b, the general pattern is similar. A first branch showing very strong Li depletion appears, especially for the case of the Pleiades. This branch, which initially formed at \( v \sin i \sim 30 \text{ km s}^{-1} \), is then followed by very Li depleted stars, all of them represented by K-type dwarf stars. A second branch, almost horizontal, with much less Li depleted values appears, formed essentially by F-type stars. However, in this horizontal branch, some examples of rare, very fast rotators G- and K-type stars are present, indicating a normal stratification of some Li depleted values. In the next subsection we discuss this effect in more detail.

### 3.2.3. The nature of some very rapid rotators in associations: Projected versus equatorial rotation velocities

An important work that helps us to understand the effects of rotation in associations is that of Messina et al. (2010). For these associations they measured the photometric stellar rotation periods and, at the same time, they estimated the stellar velocities in all of its components. Each association is distinguishable by the similar space velocities, an important feature appears in Fig. 4. This is the presence of a minimum of the Li depletion corresponding to the rotational velocity of \( v \sin i \sim 50 \text{ km s}^{-1} \). For even larger velocities, FG-type stars are distributed in an almost horizontal sequence. Instead, K-type dwarf stars show a much more important Li depletion for very rapid stellar rotators. As we explain in the next subsection, older stellar groups present different behaviours regarding this general stellar distribution of the LRC.

![Fig. 4. A(Li) vs. \( v \sin i \) of genuine stars in the associations Tuc-Hor (red filled circles), Columba (green open circles), and Carina (blue filled triangles). Intruding stars not considered in this work are shown as black squares overlapping the different symbols. All A(Li) values are maintained as presented by the authors (da Silva et al. 2009). The spectral types are indicated for rapid stellar rotators.](image-url)
radii by comparing the star positions in a colour-magnitude diagram with evolutionary tracks. This data enabled them to calculate the equatorial rotation velocities for the individual stars as $V_{eq} = 2π(R/P)$, where $R$ is the stellar radius and $P$ the rotation period. Figure 5 in Messina et al. (2010) represents a diagram of observed projected $v\sin i$ velocities versus the calculated and measured $V_{eq}$ velocities. It is interesting to note that in general, for $v\sin i$ or $V_{eq}$ values less than ~50 km s$^{-1}$, a large part of the individual points pertaining to several associations are placed near the diagonal defined by $v\sin i = V_{eq}$, corresponding to equator-on orientation. This figure shows, however, a fraction of stars with $V_{eq}$ velocities higher than the corresponding $v\sin i$ values. In other words, the projected observed $v\sin i$ velocities underestimate the real $V_{eq}$ velocities. Because stellar radii are fixed, this means that some stars are rotating faster, due to shorter periods, than would be indicated by the $v\sin i$ values.

In Fig. 6 we use a different type of representation that helps us to distinguish among the faster rotators and which types of stars deplete their Li more rapidly. In this figure the estimated stellar radii taken from Messina et al. (2010) for associations ABDA, THA, COA, and CAA are presented against the projected $v\sin i$ observed values. For higher values of $v\sin i$ (equivalent to real higher $V_{eq}$ values) the corresponding stellar radii are between 0.8 and 1.0 $R_{\odot}$, which represents well the radius values of K-type dwarf stars. These stars normally deplete their Li faster than FG-type stars in the rapid rotator zone due to their larger CZ.

4. The lithium desert

The existence of a specific and a relatively small region in the general A(Li)-$T_{eff}$ stellar map, apparently devoid of field stars, was proposed by Ramírez et al. (2012), hereafter RA12 and was called the lithium desert, defined by the interval $5950 < T_{eff} < 6100$ K and $1.55 < A(Li) < 2.05$. The existence of such a region was inspired by the work of Chen et al. (2001), which found an empty area centred at $A(Li) \sim 1.5$. This zone was separated by a bi-modal distribution of Li-rich and Li-poor stars. They considered, due to a strong correlation among low-Li stars of the Li dip stars between mass and [Fe/H] found by Chen et al. (2001), that this could also be the case on the low-Li side of the empty area. In this sense, according to this, the low-Li side could contain evolved Li dip stars.

This apparent connection with Li dip stars was discussed in RA12, indicating that a relation between mass and [Fe/H] on the higher Li side also exists, and this was found using the same data of Chen et al. (2001). At the same time, RA12 found, this time using their own data, that a similar mass-metallicity relation exists in the lower Li zone, but with a somewhat larger dispersion. All these properties led RA12 to consider that the contribution of evolved Li dip stars might not be important.

Nevertheless, the main problem consisted in answering the question of what causes this Li desert. A process of a rapid and not-yet-identified Li depletion mechanism could then exist in order to explain the complete absence of stars in this intermediate void region. A more recent research by AG18 using twice the number of stars in RA12, studied in detail the problem of the lithium desert. They proposed that both scenarios (evolved Li dip population and a severely Li depleted region) were partially correct. In any case, in both works (RA12 and AG18), the problem of how to explain the physical reason of this apparent absence of stars in the Li desert remained. We note, however, that AG18 found two apparently normal stars (one without planets, HD 90422, and another with planets, HD 31253) located in the box (hereafter Box) of the Li desert.

In addition to AG18 there are other authors who have found the presence of stars inside this Box, for example López-Valdivia et al. (2015), who detected three stars inside the lithium desert:
BD+47, HD 44985, and #58440 of the OC M4 ([MVB2012] 58440). Consequently, it seems that the Li desert is not completely empty of stars. This hypothesis became a reality, because as a result we identify that several stars could be present in the Box corresponding to the Li desert. We detect some ‘new’ stars belonging to the Box by the means of new $T_{\text{eff}}$ values furnished by space observatories as Gaia.

In a certain way, this is a challenging problem due to the reduced size of this Box, meaning that sufficiently reliable $T_{\text{eff}}$ values must be used in order to know if a star belongs to the Box or not. In this analysis we only consider stars with a mean uncertainty less than or equal to $0.1$ for the A(Li) and $150$ K for the effective temperatures. We calculated the average between the maximum and minimum values of temperature, this is $(B_{\text{T}_{\text{eff}}} - b_{\text{T}_{\text{eff}}})/2$, using the uncertainties given by Gaia described in Sect. 2. We note that the value of an error of $150$ K is near the size in $T_{\text{eff}}$ of the Box. Dividing into the Gaia DR2 catalogue, which has a large variety of $T_{\text{eff}}$ errors for individual stars, we found several candidates that are considered as the basis of our approach.

We detect 13 stars in the Box with a mean uncertainty in $T_{\text{eff}}$ of less than $150$ K. Due to these uncertainties, several of them can be in or out of the Box. We detected 17 stars outside the Box, but due to their individual $T_{\text{eff}}$ uncertainties (150 K), could go into the Box (see Table 3). We refer these stars as ‘near-Box’ in the last column of Table 3. From the total of 30 stars that can participate in this enter-exit balance, there are 24 stars without detected planets and 6 planetary host stars. We note that the detected 17 stars out of the Box are all stars with $T_{\text{eff}}$ values smaller than the cool limit $T_{\text{eff}}$ of the Box (i.e., $T_{\text{eff}} = 5950$ K).

We also explore for candidates that could enter the Box with values larger than the hot limit of $T_{\text{eff}} = 6100$ K. We found seven candidates with maximum values of $T_{\text{eff}}$ near 6300 K. Nevertheless, all of them have mean uncertainties in $T_{\text{eff}}$ larger than $150$ K, and thus do not fulfill the conditions to enter the Box in this analysis.

When we analyse the two stars in the Box detected by AG18 by means of Gaia DR2 $T_{\text{eff}}$ we obtain the following: the planet host star HD 31253 remains in all cases inside the Box, whereas the non-planetary host star HD 90422 could go out of the Box taking into account the uncertainties (see Table 1).

Figure 7a shows the distribution of the stars in the defined Box in the plane A(Li)–$T_{\text{eff}}$ within the error limit for the effective temperatures. A proportion of 6 host planet stars against 24 non-planet host stars is found, but is this a typical representative value? The answer is yes, because this rate of $0.25$ (6/24) is the same ratio that we found when considering the ~250 host planet stars in our whole catalogue divided by the approximate value of 1070 non-planet host stars. By considering the uncertainties in $T_{\text{eff}}$, more stars can enter the Box than can leave it.

Figure 7b presents a histogram of effective temperature of the stars in the sample (Table 1) with $1.55 < \text{A(Li)} < 2.05$. This is the same lithium abundance range as in the Box. For reasons of homogeneity in the comparison with the other stars in the field, the Box in the histogram of Fig. 7b contains a number of stars corresponding to the full sample; his does not take into account the errors in $T_{\text{eff}}$. For this reason, more stars appear in the bin corresponding to the Box than in Fig. 7a. It is clear in this histogram how the density of stars varies according to the range of temperature considered, dropping considerably in the Box, which is indicated in the corresponding bar. In Fig. 8 we show the whole map of A(Li) against the $T_{\text{eff}}$ (Gaia) of field stars given in Table 1. The six comparative boxes of the histogram used to see the variations in the number of stars around the Box are superimposed on the figure. From this point of view the lithium desert does not appear to be a real physical problem, but rather a statistical distribution fluctuation.

### 5. Discussion and conclusions

This paper covers two different topics. The first topic (Sect. 3) is devoted to the lithium-rotation connection (LRC) for stars with masses between $0.8$ $\text{M}_\odot$ and $1.4$ $\text{M}_\odot$, and stellar types from F5 up to K4. The most important manifestation of the LRC is that for very low stellar rotations, stars appear to be in general Li-poor, whereas they appear Li-rich for larger rotations. The second topic (Sect. 4) refers to the existence or not of what is known in the literature as the lithium desert appearing in the general distribution of the lithium abundance A(Li) of these stars as a function of effective temperatures $T_{\text{eff}}$ (Fig. 2).

We summarise what we have learned over this study of the lithium-rotation connection. The first new result consists of an evident velocity. A more detailed approach.

| Star      | $T_{\text{eff}}$ (K) | $b_{\text{T}_{\text{eff}}}$ (K) | $B_{\text{T}_{\text{eff}}}$ (K) | A(Li) | Planet Located |
|-----------|----------------------|----------------------|----------------------|--------|---------------|
| HD 208    | 5801 5865 6157 | 2.00 ± 0.10 | N                | Box               |
| HD 7134   | 5975 5858 6038 | 1.98 ± 0.10 | N                | Box               |
| HD 31253  | 6025 5961 6109 | 1.75 ± 0.02 | Y                | Box               |
| HD 36108  | 5982 5899 6033 | 1.96 ± 0.02 | N                | Box               |
| HD 38510  | 5925 5855 6082 | 2.02 ± 0.02 | N                | Box               |
| HD 83529  | 6004 5920 6048 | 1.94 ± 0.02 | Y                | Box               |
| HD 86081  | 5973 5878 6042 | 2.00 ± 0.08 | Y                | Box               |
| HD 90081  | 6007 5970 6040 | 1.97 ± 0.10 | N                | Box               |
| HD 110897 | 5968 5927 6026 | 2.04 ± 0.11 | N                | Box               |
| HD 153627 | 5954 5926 6020 | 1.68 ± 0.02 | N                | Box               |
| HD 165499 | 5950 5916 6005 | 2.05 ± 0.10 | N                | Box               |
| HD 193193 | 5968 5906 6042 | 2.04 ± 0.02 | N                | Box               |
| HD 201496 | 5957 5875 6019 | 1.89 ± 0.15 | N                | Box               |
| HD 16382 | 5937 5893 5982 | 2.01 ± 0.10 | N                | Near-Box            |
| HD 17865 | 5886 5797 5971 | 1.73 ± 0.12 | N                | Near-Box            |
| HD 20407 | 5909 5796 5960 | 1.81 ± 0.12 | N                | Near-Box            |
| HD 31527 | 5922 5905 5986 | 1.93 ± 0.08 | N                | Near-Box            |
| HD 55575 | 5913 5866 5964 | 1.76 ± 0.10 | N                | Near-Box            |
| HD 74957 | 5899 5882 5966 | 1.89 ± 0.10 | N                | Near-Box            |
| HD 95128 | 5947 5828 6066 | 1.81 ± 0.04 | Y                | Near-Box            |
| HD 97037 | 5881 5816 5950 | 1.57 ± 0.02 | N                | Near-Box            |
| HD 114762 | 5946 5870 6030 | 2.04 ± 0.02 | Y                | Near-Box            |
| HD 117105 | 5937 5870 6031 | 1.93 ± 0.03 | N                | Near-Box            |
| HD 119173 | 5914 5793 6007 | 1.90 ± 0.12 | N                | Near-Box            |
| HD 141624 | 5915 5871 5985 | 1.57 ± 0.15 | N                | Near-Box            |
| HD 147513 | 5883 5790 5959 | 2.01 ± 0.02 | Y                | Near-Box            |
| HD 148816 | 5944 5869 6021 | 1.89 ± 0.02 | N                | Near-Box            |
| HD 198089 | 5820 5746 5967 | 1.68 ± 0.05 | N                | Near-Box            |
| HD 199289 | 5921 5885 6001 | 2.01 ± 0.10 | N                | Near-Box            |
| HD 220689 | 5944 5913 6011 | 1.93 ± 0.02 | Y                | Near-Box            |

**Notes.** Column 1: Henry-Draper catalogue name; Cols. 2–4: Effective temperatures taken from Gaia DR2 and their lower ($b_{\text{T}_{\text{eff}}}$) and upper ($B_{\text{T}_{\text{eff}}}$) limits; Col. 5: Lithium abundance; Col. 6: Presence of planets (Yes or No); and Col. 7: Location in or near the Box.
approach was then necessary to better determine this critical velocity. This was done by means of the distribution of Li abundance values versus the $v\sin i$ values adding a third axis representing other stellar parameters, which is depicted in a mosaic shown in Fig. 3.

A more realistic critical rotation velocity was found. After our analysis we conclude that those stars with $v\sin i < 5 \text{ km s}^{-1}$ (slow rotators) have different properties of age and $T_{\text{eff}}$ (especially in this parameter) than those stars with $v\sin i > 5 \text{ km s}^{-1}$ (fast rotators), either for field stars with or without planets or cluster stars. In short, the critical projected rotational velocity can be considered represented by the value of $5 \text{ km s}^{-1}$. This critical rotational velocity is representative of the lithium-rotation connection, and also separates other physical parameters.

This critical velocity is important for models that study the LRC, such as the Li depletion hydrodynamic model of Baraffe et al. (2017). In this model, the critical velocity separates the effects of penetrating plumes at the lower edge of the convection internal zone producing the Li depletion. We should note here that we also explored independently, from our data described in Sect. 2, two relevant catalogues of A(Li). First, the AMBRE/Li catalogue of Guiglion et al. (2016), which was filtered from repeated values and other inconsistencies. We finally found for this catalogue 4927 clean actual star members of which only

2300 are dwarf FGK stars. Guiglion et al. (2016) recognise a subsample of 2310 dwarf stars. A detailed discussion of this filtering process will be given in our next work in this series. The second catalogue was published by Bensby & Lind (2018) which contains 515 stars. We searched, in both catalogues, for the projected rotational velocities in the literature with the same tool as described in Sect. 2. In both samples we found approximately the same threshold critical velocities as mentioned above.

Regarding our study on the age dependency of the LRC properties, we summarise the knowledge on this subject. As mentioned in the Introduction, Bouvier et al. (2016) have detected the presence of the LRC in a very young open cluster of 5 Myr (NGC 2264). It is interesting to note that this age corresponds to the PMS stage, suggesting in this way a relation of the LRC with the very initial stellar stages of the lives of low-mass stars. In NGC 2264 the LRC is acting on stars with masses in the interval 0.5–1.2 $M_\odot$, which is similar to the interval of masses considered here (0.8–1.4 $M_\odot$). For older ages, Messina et al. (2016) detected the action of the LRC in the Beta Pic association (20 Myr), but in a clear way only for very low-mass stars between 0.3 $M_\odot$ and 0.8 $M_\odot$. For stars with masses higher than 0.8 $M_\odot$ the LRC appears only to be incipient in this association. Several doubts arose when explaining this different behaviour, but we note that both groups are in the generally poorly known spin-up stage for low-mass stars that finishes at ~30–40 Myr (Bouvier et al. 2014). The next age step of the LRC studied in the literature is that of the open cluster Pleiades (125 Myr) and of the stellar stream Pec-Eri, with an age similar to that of the Pleiades. Our contribution on the age dependency study of the LRC refers to the second and final general rotation stage, the spin down, also beginning at ~30–40 Myr and lasting forever (Bouvier et al. 2014).

For all the stellar associations studied here, we first detected and eliminated all intruder members. To do this we employed a simple chemical method by which we considered as an intruder any star member that had an individual metallicity value quite different from the mean group metallicity. For this purpose we determined these new mean group metallicities for four associations (see Sect. 3.2) for which only one metallicity association value appears in the literature. In addition, considering that the associations Tucana-Horologium, Columba, and Carina all have a similar age of 45 Myr, this signifies that they are just at the beginning of this general rotational braking stage. In
Fig. 4 we show the behaviour of A(Li) versus $\sin i$ for these three associations with their genuine stellar components, where intruder members were eliminated. In this figure, a typical pattern appears in which Li depleted stars are present for $\sin i$ values that are below a critical value $\sin i < 10 \text{ km s}^{-1}$ value.

For $\sin i$ values higher than this critical velocity, a single branch of inhibited Li depletion stars appears. This branch continues up to very large rotational values. However, a minimum Li depletion characteristic of these young associations appears at $\sin i \sim 50 \text{ km s}^{-1}$. This kind of pattern is important because in the next studied association, AB Doradus (ABDA), an extra branch of strong Li depletion appears, beginning at $\sin i \sim 30 \text{ km s}^{-1}$ and continuing up to large rotation values of $\sim 70 \text{ km s}^{-1}$ (see Fig. 5a). This new branch of very strong Li depletion, is formed by low-mass K dwarfs and their rapid Li depletion acts together according to their minimal masses. This behaviour of K-type dwarfs is in agreement with the distribution of their stellar radii with $\sin i$, as shown in Fig. 6. The other branch, composed essentially of only three FGK-type stars, follows the same pattern, as is the case of the stellar groups at 45 Myr, attaining very fast rotations, greater than $\sim 130 \text{ km s}^{-1}$. Even in this case, the only very high rapid K-dwarf rotator at $\sin i \simeq 140 \text{ km s}^{-1}$ is the only one that depletes Li. We note that this double branch depletion pattern in ABDA is also found in the Pleiades (see Fig. 5b). This similarity agrees with the fact that both the ABDA and the Pleiades have the same age (around 120 Myr) and that both stellar groups have a common origin (Ortega et al. 2007).

We understand that the formation of a second depletion branch in groups at 120 Myr is a consequence of the general diminishing of stellar rotation for that age, during the general spin-down era. We note that the birth of the first depletion branch in ABDA at $\sin i \sim 30 \text{ km s}^{-1}$ also corresponds to the minimum Li depletion of the Pleiades (see Fig. 5). This value is smaller than the value of $\sin i \sim 50 \text{ km s}^{-1}$ of the mentioned minimum Li depletion in the younger associations. We note, however, that for the open cluster Alpha Per with an age of (50–70 Myr), which is intermediate between of our considered younger associations (45 Myr) and that of ABDA (120 Myr), the Li minimum also is intermediate between of our considered younger associations.

To explore the behaviour of the LRC for older ages, we considered the open cluster NGC 1039 with an age of 250 Myr. Following the classical publication of this cluster by Jones et al. (1997), we plotted the A(Li) versus $\sin i$ values (not shown in this paper) for members with more than 75% member probability. The corresponding minimum of Li depletion corresponds to near 17 km s$^{-1}$. Separately, we confirmed this same value of $\sim 17 \text{ km s}^{-1}$ by plotting for members of NGC 1039 with more than 90% member probability, by using the A(Li) values of Sestito & Randich (2005) and $\sin i$ values compiled and described in Sect. 2. We conclude that in a period going from the age of 45 Myr of the younger associations considered here up to the age of 250 Myr of NGC 1039, (i.e., a 200 Myr interval), the minimum Li depletion points have shifted from the corresponding $\sin i$ value of $\sim 50 \text{ km s}^{-1}$ at 45 Myr to somewhat less than 20 km s$^{-1}$ for 250 Myr. This shift also appears to be a direct consequence of the general spin down of the star rotation behaviour. Another conclusion of this work is that K-dwarf stars are the first to deplete their Li in these early stages in the main sequence at high rotation velocities, due to their important convective zones. This behaviour is also due to the general spin down of low-mass stars. We can try to quantify this behaviour by estimating the mean $\sin i$ values for our studied stellar moving groups with ages at 45 Myr and 120 Myr. These approximate mean values of $\sin i$ are respectively equal to 32 km s$^{-1}$ and 20 km s$^{-1}$. Their ratio 32/20 = 1.6 can be compared with that expected in the general theoretical braking rotational curves for slow and fast rotators (see Fig. 7 in Bouvier et al. 2014). For these ages, the ratios are 1.6 and $\sim 2.0$, respectively, which is in agreement with the observed values of our chosen associations.

Section 4 was devoted entirely to the study of what was considered in the literature as the lithium desert. At first sight this region shows an anomalous absence of stars, which also presented an unsolved problem regarding the physical mechanism that provokes such a radical Li depletion. In reality, by means of new $T_{\text{eff}}$ values obtained from Gaia DR2, we found that the lithium desert appears to be a false problem as in this work we detected 30 stars that are in the Box defined by $\sin i$ near to it. Due to the uncertainties of the Gaia $T_{\text{eff}}$ values, from these 30 objects, 13 stars in the Box can remain or leave the box, and 17 nearby stars can enter into the box. In any case, the Box representing the lithium desert probably contain stars. A population test was made to see if a possible inference of the actual number of stars in the Box is reasonable. All this in comparison with the whole population of nearby stars in that A(Li) interval. We found that approximately 15 stars can occupy the region of what was called the lithium desert. This shows that the considered past absence of stars was more likely a result of a statistical fluctuation distribution effect.

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