Lithium in red giant stars: Constraining non-standard mixing with large surveys in the Gaia era*,**

C. Charbonnel1,2, N. Lagarde3, G. Jasiewicz4, P. L. North5, M. Shetrone6, J. Krugler Hollek6,9, V. V. Smith7, R. Smiljanic8, A. Palacios3, and G. Ottoni1

1 Department of Astronomy, University of Geneva, Chemin des Maillettes 51, 1290 Versoix, Switzerland
2 e-mail: Corinne.Charbonnel@unige.ch
3 Institut UTINAM, CNRS UMR 6213, Univ. Bourgogne Franche-Comté, OSU THETA Franche-Comté-Bourgogne, Observatoire de Besançon, BP 1615, 25010 Besançon Cedex, France
4 UMR 5299 LUPM CNRS Université Montpellier II, Place Eugène Bataillon, 34095 Montpellier Cedex 05, France
5 Institute of Physics, Laboratory of Astrophysics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland
6 University of Texas, McDonald Observatory, TX 79734, USA
7 National Optical Astronomy Observatory, Tucson, USA
8 Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Bartycka 18, 00-176 Warsaw, Poland
9 Twitter, 1355 Market Street, Suite 900, San Francisco, CA 94103, USA

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ABSTRACT

Context. Li is extensively known to be a good tracer of non-standard mixing processes occurring in stellar interiors.

Aims. We present the results of a new large Li survey in red giant stars and combine it with surveys from the literature to probe the impact of rotation-induced mixing and thermohaline double-diffusive instability along stellar evolution.

Methods. We determined the surface Li abundance for a sample of 829 giant stars with accurate Gaia parallaxes for a large subsample (810 stars) complemented with accurate HIPPARCOS parallaxes (19 stars). The spectra of our sample of northern and southern giant stars were obtained in three ground-based observatories (Observatoire de Haute-Provence, ESO-La Silla, and the McDonald Observatory). We determined the atmospheric parameters ($T_{\text{eff}}$, $\log(g)$, and [Fe/H]), and the Li abundance. We used Gaia parallaxes and photometry to determine the luminosity of our objects and we estimated the mass and evolution status of each sample star with a maximum-likelihood technique using stellar evolution models computed with the STAREVOL code. We compared the observed Li behaviour with predictions from stellar models, including rotation and thermohaline mixing. The same approach was used for stars from selected Li surveys from the literature.

Results. Rotation-induced mixing accounts nicely for the Li behaviour in stars warmer than about 4200 K, independently of the mass domain. For stars with masses lower than 2 $M_\odot$, thermohaline mixing leads to further Li depletion below the $T_{\text{eff}}$ of the RGB bump (about 4000 K), and on the early asymptotic giant branch, as observed. Depending on the definition we adopt, we find between 0.8 and 2.2% of Li-rich giants in our new sample.

Conclusions. Gaia puts a new spin on the understanding of mixing processes in stars, and our study confirms the importance of rotation-induced processes and of thermohaline mixing. However asteroseismology is required to definitively pinpoint the actual evolution status of Li-rich giants.

Key words. stars: abundances – stars: evolution – surveys – stars: late-type

1. Introduction

Along their evolution, stars modify their chemical composition through central and shell nuclear burning coupled to various internal transport mechanisms (atomic diffusion, convection, overshooting, rotation-induced mixing, thermohaline double-diffusion, and other kinds of hydrodynamic instabilities). These processes eventually modify the photospheric composition of the stars, in proportions that depend on their initial mass and metallicity, rotation velocity, mass loss, and evolutionary status.

In the case of low- and intermediate-mass stars (hereafter LIMS), Li-7 (hereafter Li) is one of the best tracers of the internal mixing mechanisms and of possible associated transport of angular momentum (e.g. Deliyannis et al. 2000; Talon & Charbonnel 2010). For cool main sequence (hereafter MS) low-mass stars (LMS, i.e., masses below ~1.2 $M_\odot$, which are relatively slow rotators, allowing for the precise determination of their Li abundance), the best constraints are the solar Li photospheric value, which is a factor of ~150 lower than the initial meteoritic value (e.g. Lodders et al. 2009; Asplund et al. 2009; Caffau et al. 2010), the Li abundance of solar-twins (e.g. King et al. 1997;
Martín et al. 2002; Do Nascimento et al. 2009; Castro et al. 2011; Monroe et al. 2013; Carlos et al. 2016), and the so-called Li dip around effective temperature of 6700 K that coincides with a sharp variation in the surface rotation rate around mid-F type in open clusters like the Hyades and older (e.g. Wallerstein et al. 1965; Boesgaard & Tripicco 1986; Boesgaard 1987; Chen et al. 2001; Cummings et al. 2017). Rotation-induced processes couple to the effects of internal gravity waves are excellent candidates for providing a consistent explanation for the behaviour of Li and that of the surface and internal rotation rate of these MS G- and F-type objects (e.g. Talon & Charbonnel 2003, 2005; Charbonnel & Talon 2005), although additional processes like atomic diffusion, mass loss, and magnetic instabilities can play a role (e.g. Michaud 1986; Richer & Michaud 1993; Schramm et al. 1990; Denissenkov 2010a; Eggenberger et al. 2012).

Complementary information on transport processes at play in LIMS comes from Li data along the subgiant and red giant branches (hereafter SGB and RGB, respectively). During these evolution phases, surface rotation is usually very low, allowing for a precise exploitation of the spectra. The low Li abundances in SGBs observed well before the occurrence of the first dredge-up (e.g. Balachandran 1995; Mallik et al. 2003; Pasquini et al. 2004; Lèbre et al. 2006; Anthony-Twarog et al. 2009) and after the end of dilution further up on the RGB (e.g. Brown et al. 1989) can be explained by rotation-induced mixing that enlarges the Li-free region inside their MS A- or F-type progenitors (e.g. Palacios et al. 2003). Later on along the RGB, the additional and sudden Li drop observed at the so-called luminosity bump (e.g. Gratton et al. 2000; Lind et al. 2009a) can be interpreted as resulting from other hydrodynamical instabilities. The most probable one is the so-called thermohaline instability, for which several alternative driving mechanisms have been proposed (“double diffusive thermohaline mode” induced by 3He-burning in the outer wing of the thin hydrogen-burning shell, Charbonnel & Zahn 2007; Charbonnel & Lagarde 2010; “magneto-thermohaline” mode driven by strong differential rotation and a poloidal magnetic field, Denissenkov et al. 2009; “cycloidal large-scale vortices” mode where rotation impacts the linear growth of the fingering instability, Sengupta & Garaud 2018; see also phenomenological prescriptions, Henkel et al. 2017).

Several works in the literature present Li abundance determinations for large samples of field stars. Most of the recent studies focused on dwarf stars, looking for possible connections (which were not found) between Li abundance and the presence of planets (Ramírez et al. 2012, 671 FGK dwarf and subgiant stars; Delgado Mena et al. 2014, 326 dwarfs; Delgado Mena et al. 2015, 353 dwarfs). Other studies explored the case of post-MS stars, starting with the pioneer work of Brown et al. (1989, 644 bright G-K giants), followed by de Laverny et al. (2003, 54 subgiant stars crossing the Hertzsprung gap), Lèbre et al. (2006, 154 bright giant stars), Luck & Heiter (2007, 286 G/K giants), Liu et al. (2014, 378 G/K giants). Recently, large surveys have led to a paradigm shift in terms of sample size. In particular, the AMBRE and GALAH surveys have yielded public catalogues with Li abundances for, respectively, ~7300 and 342,000 stars covering a large range in metallicity and evolutionary status (Guiglion et al. 2016; Buder et al. 2018; Deepak 2019). A couple of studies have also searched for Li-rich stars from the Gaia-ESO survey (Casey et al. 2016, 2019; Smiljanic et al. 2018) and the LAMOST survey (Cui et al. 2012; Singh et al. 2019).

In principle, all these data can be used to study the cumulative effects of the various processes that modify the surface Li abundance of LIMS along their evolution. However, robust conclusions require a good knowledge of the evolution status of individual stars, and a good estimate of their mass. This was the original motivation of the present work, which aimed to derive Li abundances in a volume-limited sample of field giant stars with precise HIPPARCOS parallaxes (and possibly Gaia measurements), and which are located close to or above the bump on the RGB and on the early asymptotic giant branch (AGB). Here we present the results of this observational project, and combine it with other large samples to provide robust and statistically significant constraints on stellar internal mixing processes that are suspected to be in action in LIMS along their evolution.

The paper is organised as follows. We present the selection criteria of our sample stars and determine their luminosity based on HIPPARCOS or Gaia DR2 parallaxes in Sect. 2. The observation runs and the analysis method that led to the determination of the stellar parameters and of the Li abundances are presented in Sect. 3 where we also validate our Li measurements with respect to those derived for common stars in other studies. We compare in Sect. 4 our Li data with the predictions of stellar models including rotation-induced mixing and thermohaline instability computed by some of the co-authors of the present paper (Charbonnel & Lagarde 2010; Lagarde et al. 2012). We extend the comparison to Li literature data for other samples of giant stars with HIPPARCOS parallaxes (Luck & Heiter 2007; Liu et al. 2014) or Gaia parallaxes when available (GALAH survey, Buder et al. 2018). We present our conclusions in Sect. 5.

2. Sample selection and stellar luminosities with HIPPARCOS and/or Gaia parallaxes

2.1. Initial sample selection

Our initial goal was to use Li abundances in evolved stars to constrain the cumulative effects of internal mixing processes acting both on the MS and the advanced phases of the evolution of LIMS, in addition to searching for Li-rich giants. We originally selected a volume-limited sample of stars potentially located on the RGB and the early AGB, using their HIPPARCOS parallaxes, V magnitude, and B−V and F−I colours. This sample was extracted from the first HIPPARCOS catalogue (Perryman et al. 1997), requiring that the parallax be larger than 5 mas, with a relative error of less than 10%. Bolometric corrections were derived from V−I given in the same catalogue to estimate the luminosity of the candidates. All the stars in the sample are brighter than V<8. The RGB stars were selected using V−I > 0.9 and 1.2<log(L/L⊙)<2.3, and the possible AGB stars using B − V < 1.5 and log(L/L⊙) > 2.6. We favoured these two regions of the Hertzsprung-Russell diagram (HRD) because they correspond to the location of the RGB bump and that of the early-AGB and they were thought to host most of the so-called Li-rich giants (Charbonnel & Balachandran 2000, see Sect. 4.3). To derive statistically significant features, we observed all the presumed early-AGB stars and 2/3 of the presumed RGB stars selected that way. Hence the total number of stars for which we carried out spectroscopic observations is 829 (731 probable RGBs and 98 probable AGBs).

2.2. Determination of stellar luminosities and final sample based on Gaia DR2

We computed the luminosity of our sample stars using parallaxes from Gaia DR2 (Gaia Collaboration 2018b) when available (810 stars out of 829), or from the New HIPPARCOS catalogue...
Table 1. Informations on giants stars in our sample.

| HD    | RA     | Dec    | $T_{\text{eff}}$ (K) | [Fe/H] | $\log L/L_{\odot}$ | $L/L_{\odot}$ | $\log g$ | $\pi_{\text{Gaia}}$ | $\pi_{\text{Hipparcos}}$ | log($L/L_{\odot}$) | $\sigma_{\log L/L_{\odot}}$ | $\sigma_{\log g}$ | $\sigma_{\log L/L_{\odot}}$ | $\sigma_{\log g}$ | $e_{\log g}$ | Mass | $e_{\log g}$ | $e_{\log L/L_{\odot}}$ | $e_{\log L/L_{\odot}}$ |
|-------|--------|--------|---------------------|--------|-------------------|--------------|--------|---------------------|---------------------|-------------------|-------------------------|---------------|-------------------------|---------------|--------|------|----------------|----------------|
| 87    | 1.4248883 | 13.396266 | 5110 | 90 | 0.23 | 0.1 | 0.1 | 8 | 0.75 | 0.3 | 0.39 | 0.03 | 8.214 | 0.1339 | 0.03 | 0.03 | 2.99 | 0.5 | 0.01 |
| 645   | 2.6784778 | -12.579989 | 4980 | 130 | 0.28 | 0.1 | 0.1 | 0 | 3.33 | 0.35 | 1.43 | 0.03 | 13.881 | 0.0803 | 1.40 | 0.02 | 1.9 | 0.4 | 0.6 |
| 1013  | 3.6506583 | 20.206701 | 3600 | 150 | 1.24 | 0.0 | -1 | 1.1 | 8.86 | 0.22 | 2.98 | 0.02 | 9.1895 | 0.4342 | 3.01 | 0.06 | 1.52 | 0.71 | 1.46 |
| 1483  | 4.6737424 | -43.255579 | 4420 | 110 | 0.56 | 0.1 | 0.1 | 0 | 8.23 | 0.3 | 1.75 | 0.05 | 7.3177 | 0.0392 | 1.88 | 0.02 | 1.18 | 0.31 | 0.67 |
| 2261  | 6.651046 | -42.305989 | 4770 | 250 | 0.37 | 0.4 | 0.2 | 0.3 | 8.58 | 0.73 | 1.92 | 0.02 | 0.00009990 | 1.93 | 0.02 | 1.57 | 0.49 | 1.16 |
| 2529  | 7.1799697 | -50.532864 | 4650 | 110 | 0.43 | 0.1 | 0.3 | 0 | 7.98 | 0.43 | 1.76 | 0.05 | 8.4914 | 0.0322 | 1.72 | 0.02 | 1.41 | 0.46 | 1.08 |
| 3712  | 10.2126638 | 56.333738 | 4510 | 90 | 0.51 | 0.4 | 0.1 | 0 | 14.29 | 0.15 | 2.99 | 0.01 | 1.6949 | 1.2847 | 4.38 | 0.08 | 0.92 | 0.01 | 0.0 |
| 3750  | 9.9646577 | -44.796269 | 4610 | 110 | 0.45 | 0.0 | 2.5 | 0 | 10.62 | 0.43 | 1.63 | 0.04 | 10.2314 | 0.0499 | 1.67 | 0.02 | 1.49 | 0.5 | 1.0 |
| 4042  | 11.012434 | 70.283425 | 5020 | 120 | 0.26 | 0.3 | 1.1 | 0 | 6.8 | 0.32 | 1.64 | 0.04 | 6.9532 | 0.0288 | 1.62 | 0.02 | 2.0 | 0.9 | 0.5 |
| 4211  | 11.0394114 | -38.421664 | 4600 | 100 | 0.46 | 0.0 | 0.0 | 0 | 9.63 | 0.4 | 1.76 | 0.04 | 10.1675 | 0.0691 | 1.72 | 0.02 | 1.54 | 0.5 | 0.96 |
| 4229  | 9.1145577 | -85.700074 | 4340 | 90 | 0.46 | 0.0 | 0.0 | 0 | 9.64 | 0.32 | 1.75 | 0.04 | 7.0051 | 0.0025 | 1.75 | 0.02 | 1.09 | 0.26 | 0.71 |
| 4496  | 11.65577 | -57.927643 | 4510 | 90 | 0.51 | 0.1 | 0.0 | 0 | 6.71 | 0.57 | 1.56 | 0.08 | 4.912 | 0.0522 | 1.83 | 0.03 | 1.44 | 0.43 | 1.05 |
| 4585  | 11.939084 | -18.066138 | 4210 | 110 | 0.7 | 0.2 | 0.5 | 0.1 | 9.18 | 0.41 | 1.97 | 0.04 | 8.8769 | 0.1143 | 2.03 | 0.03 | 1.02 | 0.21 | 0.64 |
| 5316  | 13.811125 | 24.557662 | 3400 | 150 | -0.3 | 0.4 | -1.3 | 1.1 | 5.73 | 0.42 | 3.18 | 0.07 | 4.5201 | -1.855 | 3.40 | 0.05 | 1.31 | 0.6 | 1.66 |
| 5395  | 14.166272 | 59.181107 | 5030 | 260 | -0.26 | 0.4 | 0.0 | 0 | 16.32 | 0.23 | 1.73 | 0.02 | 17.2875 | 0.188 | 1.72 | 0.02 | 1.9 | 0.89 | 0.6 |
| 5457  | 13.731563 | -69.527068 | 4680 | 90 | 0.42 | 0.0 | 0.0 | 0 | 14.77 | 0.27 | 1.55 | 0.02 | 14.6214 | 0.0817 | 1.58 | 0.02 | 1.59 | 0.65 | 0.9 |
| 5722  | 14.882782 | -11.379975 | 5100 | 120 | -0.24 | 0.0 | 0.0 | 0 | 10.2 | 0.53 | 1.73 | 0.05 | 9.7632 | 0.1129 | 1.79 | 0.02 | 2.49 | 0.56 | 0.5 |
| 6559  | 16.530999 | -23.992245 | 4780 | 90 | 0.39 | 0.1 | 0.0 | 0 | 8.52 | 0.44 | 1.75 | 0.05 | 8.6661 | 0.0576 | 1.72 | 0.02 | 1.59 | 0.75 | 0.9 |

Notes. flag_{L_e} indicates the determination and the upper limit of Li abundances (0 and 1, respectively). flag_{Gaia} indicates the method used to compute the luminosity log($L/L_{\odot}$) (0: $\pi_{\text{Gaia}}$ + $\pi_{\text{Hipparcos}}$; 1: $\pi_{\text{EO}}$ + $\pi_{\text{Hipparcos}}$; 2: $\pi_{\text{EO}}$ + $\pi_{\text{V}}$; 3: $\pi_{\text{DR2}}$ + $\pi_{\text{V}}$). $e_{\log g}$ and $e_{\log L/L_{\odot}}$ correspond to the error on the mass determination at $-1\sigma$ and $+1\sigma$, respectively. The full table is available at the CDS.
For each star, the effective temperature \( T_{\text{eff}} \) was determined by using both \( B-V \) and \( V-I \) colours from the New HIPPARCOS catalogue (van Leeuwen 2007) and the colour-temperature relations for F-K giants from Houdashelt et al. (2000). For the coolest stars (\( T_{\text{eff}} \leq 4000 \) K) we used Alonso et al. (1999). reddening was low for typical distances of the order of 100 pc and can be neglected as done by Luck & Heiter (2007). The error on \( T_{\text{eff}} \) was estimated from an interpolation processing in the Houdashelt tabular data assuming 2.0 \( \lesssim \log g \lesssim 3.0 \). The stellar effective temperatures and the corresponding errors are given in Table 1 and they are used across different figures throughout the paper. We compare our values for the effective temperature with those of Gaia DR2 (Gaia Collaboration 2018b) in Fig. 3. As expected, the largest differences are found among the coolest stars with effective temperature below \( 4000 \) K (see e.g. Andrae et al. 2018; Arenou et al. 2018). The cut at \( 4000 \) K mentioned above in our \( T_{\text{eff}} \) calibration procedure also reinforces the observed discrepancies in Fig. 3.

For the spectra analysis we consider bolometric magnitude \( M_{\text{bol}} \) and gravity \( \log(g) \) as given by \( M_{\text{bol}} = V - 3.1 E(B-V) + BC(V) + 5 \log(\pi) + 5 \) and \( \log(g) = \log(M) + 0.4M_{\text{bol}} + 4 \log(T_{\text{eff}}) - 12.505 \) using the 1997 HIPPARCOS parallax \( \pi \) and \( M = 2 M_{\odot} \) for all G-K giant stars; the error on \( \log(g) \) comes essentially from the error on mass.

### 3.3. Determination of [Fe/H] and of Li abundances

All spectra and calibration files were processed with the MIDAS package. For each star, a series of synthetic spectra with effective temperature \( log(T_{\text{eff}}) \) and gravity \( \log(g) \) derived as described in Sect. 3.2 and with various metallicities \( -0.6 \leq [\text{Fe/H}] \leq 0.2 \) were calculated between 665 and 675 nm with tools from the Uppsala Stellar Atmospheres Group (Gustafsson et al. 2008). The MARCS model atmospheres used here are line-blanked local thermodynamic equilibrium (LTE) models that include spherical symmetry, the opacity sampling treatment of line opacities, a chemical equilibrium extended to a few hundred molecular species, opacity for TiO and H\(_2\)O, and updates of the continuous and atomic opacities (Gustafsson et al. 2008).

We adopted a uniform micro-turbulent velocity of 2.0 km\( \text{s}^{-1} \) for all synthetic spectra. The model spectra use the line list around 671 nm extensively described by Lèbre et al. (1999). With the help of the computed synthetic spectra, some short spectral windows where the continuum approaches unity were identified in our observed spectra and used to draw the continuum. After the normalisation of observed spectra by their continuum, corrections for radial velocities were performed by using a MIDAS cross-correlation procedure between observed and synthetic spectra. Mean metallicity and Li abundance are determined for each star by the best fit between the normalised spectrum and synthetic spectra: \([\text{Fe/H}] \) was at first derived from metallic lines (mostly from about thirty Fe lines between 665 and 675 nm), and then \( A(\text{Li})^1 \) is derived from the resonance Li\( I \lambda 670.8 \) nm line. The error on the mean metallicity estimated from the fit of the iron lines found in the vicinity of the Li line is around 0.1 dex. The final adopted uncertainty of the Li abundance is around 0.2 dex.

Abundances of Li and \([\text{Fe/H}] \) values are given in Table 1. An indication of the Li range for all individual stars is presented in the HRD in Fig. 4. \([\text{Fe/H}] \) values are shown as a function of effective temperature in Fig. 5. Respectively 79.2, 20.6, and 0.2% of our sample stars have \(-0.2 \leq [\text{Fe/H}] \leq +0.2 \), \([\text{Fe/H}] \leq -0.2 \), and \([\text{Fe/H}] > +0.2 \) (29% of the total have \([\text{Fe/H}] = 0 \).

The Li abundances given here are computed in LTE. We are aware that non-LTE (NLTE) effects are not negligible, especially on the Li\( I \lambda 6708 \) line used here for abundance determination. Lind et al. (2009b) have computed NLTE corrections for giants

\footnote{1 \( A(\text{Li}) = \log (\frac{X(\text{Li})}{X(\text{He})}) + 12 \), with \( X(\text{Li}) \) the lithium mass fraction.}
Fig. 3. Comparison between effective temperature determined here and that published in Gaia DR2 for our sample stars (same symbols as in Fig. 2). Dashed-dotted lines represent a difference of 150 K in $T_{\text{eff}}$.

Fig. 4. Indication of range in Li content (LTE; colour-labelled; circles are for abundance determinations and triangles are for upper limits) derived in this work for all individual stars of our sample with their positions in HRD. Luminosities are computed as in Fig. 1 (see text for more).

with $T_{\text{eff}}$ between 4000 K and 8000 K and various metallicities, surface gravities, and Li abundances. We did not apply these corrections to our LTE abundances, particularly as we would have had to extrapolate them for stars with $T_{\text{eff}} < 4000$ K, that is, for about 10% of our sample. Furthermore, the grid covers Li abundances down to $A(\text{Li}) = -0.3$, while our observed abundances or upper limits are lower than this value for several tens of stars. As shown by Liu et al. (2014), the NLTE correction $\Delta_{\text{NLTE}} = A_{\text{NLTE}} - A_{\text{LTE}}$ depends above all on $T_{\text{eff}}$: while $\Delta_{\text{NLTE}}$ amounts to only about 0.1 dex for $T_{\text{eff}} \geq 5200$ K, it reaches about 0.3 dex at $T_{\text{eff}} = 4500$ K. For cooler stars, which represent roughly 1/3 of our sample, Table 2 of Lind et al. (2009b) displays NLTE corrections as large as 0.33 dex for solar metallicity stars with $T_{\text{eff}} = 4000$ K, log $g = 2.0$, [Fe/H] = 0.0 and $A(\text{Li}) = 0.0$ (for a 2 km s$^{-1}$ microturbulence). For higher effective temperatures, the corrections are smaller but always positive as long as $A(\text{Li}) \leq 2.7$. In other words, our LTE Li abundances underestimate the true abundances by a few tenths of a dex at most. We will comment this briefly in Sect. 4.

3.4. Comparisons with other studies

We have two, eight, and eighty two stars, respectively, in common with the samples of de Laverty et al. (2003), Lèbre et al. (2006), and Luck & Heiter (2007). We have nine stars in common with the Li sample of the AMBRE project (Guiglion et al. 2016); however the stellar effective temperatures are not provided in this study, and only two out of the nine common stars have had their [Fe/H] values published after being determined with AMBRE tools (Mikolaitis et al. 2017). We have no stars in common with the samples of Brown et al. (1989), Liu et al. (2014), nor the large GALAH survey (Buder et al. 2018).

We show in Fig. 6 the comparison between our LTE Li results and the LTE Li values of the above-mentioned papers which include the same stars (see caption for details). We also compare the effective temperature values (since the Li abundance is more sensitive to this parameter than to others, and because $T_{\text{eff}}$ is important in the comparison with stellar models, see Sect. 4.2) and the [Fe/H] values.

Our Li and $T_{\text{eff}}$ determinations agree fairly well (within less than 0.2 dex and 150 K respectively) with those derived by Luck & Heiter (2007) through their photometric pipeline. This was expected since we used the same photometric processing (calibration using observed $B - V$ and Houdashelt et al. 2000 models for the determination effective temperature) and the same MARCS models for determining the Li abundances. Larger differences exist, however, between our analysis and the works of Lèbre et al. (2006) and de Laverty et al. (2003). These two studies relied on stellar parameters from the literature, which might have introduced some heterogeneity in their analysis; additionally, Lèbre et al. (2006) report smaller S/N than we do here (>50 for northern stars, >80 for southern stars), and their Aurélie
Table 2. Informations on giants stars in three other samples used in this study.

| Name   | $T_{\text{eff}}$ | $\pi_{\text{Gaia}}$ | $e(\pi_{\text{Gaia}})$ | $\log(L/L_\odot)$ | $e(L)$ | Mass ($e(M[-1\sigma])$) | $e(M[+1\sigma])$ |
|--------|------------------|----------------------|-------------------------|-------------------|--------|--------------------------|-----------------|
| Luck & Heiter (2007) | 448  | 4840  | 10.9923 | 0.1299 | 1.74 | 0.03  | 2.49 | 1.1 | 0.5 |
|        | 3411 | 4657  | 8.7765  | 0.0385 | 1.71 | 0.02  | 2.49 | 1.28 | 0.5 |
|        | 3546 | 5102  | 19.4949 | 0.2307 | 1.71 | 0.03  | 2.0  | 1.09 | 0.5 |
|        | 4732 | 5021  | 17.2961 | 0.3842 | 1.87 | 0.04  | 2.49 | 0.95 | 0.9 |
|        | 5722 | 4995  | 9.7623  | 0.112  | 1.80 | 0.03  | 2.49 | 0.84 | 0.5 |
|        | 6037 | 4669  | 10.688  | 0.044  | 1.42 | 0.02  | 1.59 | 0.6  | 0.9 |
|        | 6186 | 4955  | 17.2961 | 0.3842 | 1.87 | 0.04  | 2.49 | 0.95 | 0.9 |
|        | 7106 | 4748  | 28.6441 | 0.413  | 1.72 | 0.03  | 1.79 | 0.94 | 1.19 |
| Liu et al. (2014) | 87   | 5072  | 8.214   | 0.1339 | 1.97 | 0.03  | 2.99 | 0.5  | 0.01 |
|        | 360  | 4850  | 8.9376  | 0.0836 | 1.74 | 0.03  | 2.48 | 1.5  | 0.5 |
|        | 448  | 4780  | 10.9923 | 0.1299 | 1.75 | 0.03  | 2.48 | 1.46 | 0.5 |
|        | 587  | 4893  | 17.3901 | 0.1339 | 1.21 | 0.02  | 1.7  | 0.5  | 0.3 |
|        | 645  | 4880  | 13.881  | 0.0803 | 1.41 | 0.02  | 2.0  | 0.5  | 0.5 |
|        | 1239 | 5114  | 4.7303  | 0.0955 | 2.36 | 0.03  | 3.98 | 1.0  | 0.02 |
|        | 1367 | 4982  | 8.875   | 0.0419 | 1.65 | 0.02  | 2.49 | 0.7  | 0.5 |
|        | 1419 | 4888  | 8.5872  | 0.1468 | 1.73 | 0.03  | 2.49 | 0.6  | 0.5 |
|        | 2114 | 5230  | 5.4912  | 0.0949 | 2.20 | 0.03  | 2.99 | 0.01 | 1.0 |
|        | 2952 | 4844  | 9.054   | 0.0535 | 1.75 | 0.02  | 2.49 | 1.39 | 0.5 |
|        | 3421 | 5287  | 3.5023  | 0.1105 | 2.73 | 0.04  | 3.97 | 0.01 | 0.99 |
| GALAH Buder et al. (2018) | 4634991546064263040 | 4064 | 0.255 | 0.0193 | 2.55 | 0.08 | 1.24 | 0.44 | 1.24 |
|        | 4644232799560251776 | 4052 | 0.2225 | 0.0243 | 2.43 | 0.11 | 1.0  | 0.23 | 0.87 |
|        | 46426346114384640 | 4176 | 0.1932 | 0.0271 | 2.29 | 0.14 | 0.92 | 0.15 | 0.93 |
|        | 4622338434971333248 | 4388 | 0.3384 | 0.0196 | 1.93 | 0.07 | 0.98 | 0.2  | 0.55 |
|        | 462233316686362752 | 4065 | 0.2681 | 0.0262 | 2.57 | 0.10 | 1.46 | 0.63 | 1.26 |
|        | 295645840340497712 | 4461 | 0.1282 | 0.0167 | 2.36 | 0.13 | 1.11 | 0.34 | 1.36 |
|        | 4827417673666050816 | 4188 | 0.2602 | 0.0192 | 2.26 | 0.08 | 1.02 | 0.21 | 0.83 |
|        | 482814201206784896 | 4291 | 0.2295 | 0.0208 | 2.19 | 0.10 | 1.65 | 0.76 | 1.34 |
|        | 289017565059498048 | 4050 | 0.1305 | 0.0227 | 2.99 | 0.17 | 2.47 | 1.55 | 1.49 |
|        | 2890162456454924544 | 4434 | 0.1656 | 0.0271 | 2.45 | 0.16 | 2.99 | 1.29 | 1.98 |
|        | 2893967522602401792 | 4391 | 0.2155 | 0.0234 | 2.24 | 0.11 | 2.48 | 1.38 | 1.5 |

Notes. We use HD number to identify stars observed by Luck & Heiter (2007) and Liu et al. (2014) while the Gaia identify is used for the GALAH sample. The full table is available at the CDS.

4. Comparison with stellar model predictions

4.1. Mass range and evolution status of the sample stars

In order to test model predictions for the Li behaviour along stellar evolution with respect to observations, we need to estimate the mass of individual stars. For this, we applied the following method to our sample and to the samples of Luck & Heiter (2007), Liu et al. (2014), and Buder et al. (2018). We use a maximum-likelihood technique adapted from Valle et al. (2014) that compares the effective temperature, luminosity, and $[\text{Fe}/H]$ of individual stars to theoretical evolution tracks in the HRD. The interpolation is done between the standard models (without rotation) of Lagarde et al. (2017, 2019) that are available for a range of masses between 0.6 and 6 $M_\odot$. The mass estimate accounts

spectra for northern stars have a lower resolution (45 000 instead of 70 000), but their CES@CAT spectra have a higher resolution than ours (95 000). The study of de Laverny et al. (2003) relies on the same observational material.

The bottom panel of Fig. 6 shows that our estimates of $[\text{Fe}/H]$ tend to be lower than those of other authors by about 0.1 to 0.3 dex. The explanation for that difference certainly lies in the 2.0 km s$^{-1}$ micro-turbulence value we adopted, and which is larger by about 0.3 km s$^{-1}$ on average than the typical values determined by Luck & Heiter (2007). Indeed, a larger micro-turbulent velocity results in a lower abundance, since the resulting synthetic lines are less saturated. The other two works involved in Fig. 6 adopted $v_{\text{turb}} = 2.0$ km s$^{-1}$ but their contribution amounts to only 10 stars instead of 82 for Luck & Heiter (2007).
mass for giant stars only (1734 stars). Because evolved stars lie in the region of the HRD where all the evolution tracks converge, and because of non-negligible error bars in effective temperature, luminosity, and metallicity, the masses we derive are relatively uncertain, as shown by the error bars we derive. None of the sample stars has an astroseismic mass. Fortunately, very precise determination of the stellar mass of individual stars is not mandatory for this work, as we shall simply compare the Li abundance of stars in different domains of mass with the corresponding model predictions (Sect. 4.2).

Our sample covers the largest mass and advanced evolution ranges (compare Figs. 8–10). It contains stars with masses between ~0.8 and 6 M$_\odot$, and evolution stages from the end of the Hertzsprung gap to the early-AGB, the majority lying in the region of the RGB bump and of the clump, and on the upper part of the RGB, as a result of our selection criteria. On the other hand, the samples of Luck & Heiter (2007) and Liu et al. (2014) focus on a more restricted mass range (between 1.5 and 4 M$_\odot$, and between 1.7 and 5 M$_\odot$ respectively; Fig. 9). Additionally, most of their stars appear to lie around the clump, although Luck & Heiter (2007) also include LIMS (1.25 to 2 M$_\odot$) located between the MS turnoff and the RGB base. Finally, GALAH sample (Fig. 10) contains many MS stars, as well as low-mass evolved stars with luminosities much lower than that of the RGB tip.

4.2. Li behaviour – The impact of rotation-induced mixing and thermohaline mixing

We compare the Li behaviour of our sample stars and of the samples of Luck & Heiter (2007), Liu et al. (2014), and GALAH (Buder et al. 2018) with the predictions from the grid of rotating stellar models of Lagarde et al. (2012). These models take into account thermohaline mixing as described by Charbonnel & Zahn (2007) and Charbonnel & Lagarde (2010), and rotation-induced processes following the formalism by Zahn (1992) and Maeder & Zahn (1998). The initial rotation velocities assumed in the computations were chosen to lead to a good agreement with the observed range of rotation velocities in field and open cluster MS stars in the mass range of our sample (Gaige 1993; Zorec & Royer 2012; see Charbonnel & Lagarde 2010; Lagarde et al. 2012 for details). The corresponding

Fig. 6. Top: comparison between LTE Li abundances determined in this work and LTE Li abundances published in studies of de Laverny et al. (2003, green), Lèbre et al. (2006, blue), Luck & Heiter (2007, black), and Guiglion et al. (2016, red). We exclude the stars with upper limits for Li published in the literature, but we include our upper limits in the case of real determinations by the other studies. Middle and bottom: comparison with effective temperature and [Fe/H] values of same studies when available. For the sample of Luck & Heiter (2007), they show their photometric and spectroscopic effective temperatures and corresponding Li and [Fe/H] values (open and full black circles). Dotted lines represent a difference of 0.1 dex in Li and [Fe/H], and of 150 K in $T_{\text{eff}}$. for the errors in effective temperature and luminosity given in Table 1 for our sample stars, as well as for the errors given in the original papers for the other samples; for all the samples we assume [Fe/H] error of 0.1 dex. The values we derived for the mass and the corresponding uncertainty are given in Table 1 (see also Fig. 7) for our sample stars and in Table 2 for the three other samples. For the GALAH survey, we derived the stellar

Fig. 7. Current masses of our sample stars as derived in Sect. 4.1.
Fig. 8. Position of our sample stars in HRD with colour-labelled indication of Li (LTE) range as in Fig. 4. The sample is split in two metallicity ranges ([Fe/H] above and below −0.2 dex, left and right respectively). The theoretical evolution tracks of the standard models (no rotation) of Lagarde et al. (2012) are superimposed for stars with masses between 1 and 6 M⊙ computed with [Fe/H] = 0 and −0.56 dex (left and right, respectively); we removed the two outliers with errors on the parallax larger than 70%.

Fig. 9. Same as Fig. 8 but for samples observed by Luck & Heiter (2007, LTE, left) and Liu et al. (2014, NLTE, right, with crosses indicating planet host stars). Here we show only their stars with −0.2 ≤ [Fe/H] ≤ +0.2 that have Gaia DR2 parallaxes (290 and 375 stars for Luck & Heiter 2007; Liu et al. 2014, respectively). Evolution tracks are the standard models of Lagarde et al. (2012) computed with [Fe/H] = 0.

evolution tracks are very similar to the standard tracks used in Sect. 4.1 to estimate the mass and evolution stage of the sample stars, hence no correction is needed with respect to these two quantities. However, thermohaline and rotation-induced mixing processes are necessary to account for the Li behaviour along the explored evolution sequence over the entire mass range considered. This is shown in Figs. 11–16, where the model predictions are compared to the Li observations, with effective temperature as a proxy for the evolution from the subgiant branch to the advanced phases (i.e., from high towards low temperatures). Standard model predictions are also shown for discussion. In each figure panel, we select stars in a given mass and metallicity range, and compare them with the relevant theoretical tracks that are shown from the zero age main sequence up to the AGB phase.

4.2.1. Our sample

Let us focus first on our own sample, which we split in two metallicity ranges. In Fig. 11 we gather the Li data for our
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Fig. 10. Same as Fig. 8 for GALAH sub-samples with high accuracy or level of confidence in NLTE Li abundance (i.e. with FlagCannon = 0 and FlagLi ≤ 1) and derived stellar parameters (Gaia DR2 parallaxes with errors less than 20%, and errors on $T_{\text{eff}}$ less than 150 K), and with $-0.2 \leq [\text{Fe/H}] \leq +0.2$ and $[\text{Fe/H}] < -0.2$ (left and right respectively). Evolution tracks are the standard models of Lagarde et al. (2012) computed with $[\text{Fe/H}] = 0$ (left), and $[\text{Fe/H}] = 0$ and $-0.56$ (right, dashed and solid respectively).

Fig. 11. Li data (LTE) for our solar-metallicity subsample ($-0.2 \leq [\text{Fe/H}] \leq +0.2$; circles and triangles: Li determinations and upper limits) as a function of effective temperature as proxy for evolution (from high to cool values). Tracks show the predictions for Li behaviour as the stars evolve from the subgiant branch to the RGB tip and later from the clump to AGB phase from the non-rotating models with thermohaline mixing (solid) and the models including rotation and thermohaline mixing (dashed) from Lagarde et al. (2012). In the left and right panels we plot respectively the stars with masses $\leq$ and $> 2 M_\odot$ and compare them with models of relevant initial stellar masses.

sample stars with $[\text{Fe/H}]$ between $+0.2$ and $-0.2$ dex (inclusive) and compare their behaviour with theoretical predictions for stellar models computed with $[\text{Fe/H}] = 0$ dex. In Fig. 12 we show the Li data for the remaining stars with $[\text{Fe/H}]$ strictly lower than $-0.2$ dex and use stellar models computed with $[\text{Fe/H}] = -0.56$ dex. Note that for these two values of $[\text{Fe/H}]$ the initial Li abundance assumed in the models is 3.11 and 2.49 dex respectively, to account for Galactic chemical evolution (e.g. Romano et al. 1999; Ryan et al. 2001; Lambert & Reddy 2004; Guiglion et al. 2016; Fu et al. 2018). In both cases we separate the stars with masses $\leq$ and $> 2 M_\odot$ and compare them with models of relevant initial stellar masses.

We first note that the Li surface evolution for the standard (non-rotating, i.e. $V_{\text{ZAMS}} = 0$) models is very similar for stars of different masses and metallicities. In this case, surface Li depletion is due solely to the first dredge-up, and it starts relatively late in the Hertzsprung gap, that is, for $T_{\text{eff}}$ between $\sim 5200$ and $5400$ K. The predicted decrease in Li due to the first dredge-up is of the order of a factor 30–60. This depletion factor depends only on the maximum depth in mass reached by the convective envelope at the end of the dredge-up. It is independent of the initial Li value assumed in the models and it hardly depends on the stellar mass and metallicity. As a consequence, the minimum Li value obtained at the end of the first dredge-up episode is of the order of $A(\text{Li}) \sim 1.3–1.6$ for the models with $[\text{Fe/H}] = 0$ and $A(\text{Li}) \sim 0.7–1$ for the models with $[\text{Fe/H}] = -0.56$. These standard predictions are in very good agreement with literature models (e.g. Iben 1967; Palacios et al. 2006; Charbonnel & Zahn 2007; Mucciarelli et al. 2010), but at odds with the data. Clearly, the surface Li depletion observed starts earlier (i.e., for higher $T_{\text{eff}}$) and is much more efficient than predicted by the standard models that account only for dilution during the first dredge-up. This confirms earlier findings (e.g. Alschuler 1975; Brown et al. 1989; Balachandran 1990; do Nascimento et al. 2000; Palacios et al. 2003).
Fig. 12. Same as Fig. 11 for our low-metallicity sub-sample ([Fe/H] < −0.2) and non-rotating models with thermohaline mixing (solid) and models including rotation and thermohaline mixing (others) of Lagarde et al. (2012) computed for [Fe/H] = −0.56. At this metallicity, the initial Li abundance assumed in the models is 2.49 dex.

Fig. 13. Same as Fig. 11 (LTE abundances) for samples observed by Luck & Heiter (2007). We show only their stars with −0.2 ≤ [Fe/H] ≤ 0.2 and compare with solar metallicity models including rotation and thermohaline mixing from Lagarde et al. (2012) computed for [Fe/H] = 0.

On the other hand, the global behaviour and the dispersion of the Li abundances observed for the entire sample at all effective temperatures are very well reproduced by the rotating models. In this case, surface Li depletion starts much earlier (i.e., at a higher effective temperature at the entrance onto the Hertzsprung gap) than in the standard models. This is due to the enlargement of the Li-free region by rotation-induced mixing while the stars are still on the MS. This also leads to more substantial Li depletion at the end of the first dredge-up event, as already anticipated with the first generation of rotating models of Palacios et al. (2003, also calculated with STAREVOL but with a less sophisticated treatment of rotation). For a given stellar mass, the higher the initial rotating rate, the lower the Li abundance all along the evolution from the MS turnoff to the RGB and the AGB. Clearly, Li data is NLTE.

Fig. 14. Same as Fig. 11 for samples observed by Liu et al. (2014); in this case, Li data is NLTE. We show only their stars with −0.2 ≤ [Fe/H] ≤ 0.2 and compare with solar metallicity models including rotation and thermohaline mixing from Lagarde et al. (2012) computed for [Fe/H] = 0.

Fig. 15. Same as Fig. 11 for GALAH subsample of giant stars with −0.2 ≤ [Fe/H] ≤ 0.2 compared to predictions of models including rotation and thermohaline mixing computed with [Fe/H] = 0. In this case, Li data is NLTE.
thermohaline mixing computed with Fig. 16. Sect. 4.2.4).

The transport coefficient is obtained with the prescription for the thermohaline diffusion coefficient “à la Ulrich & Kippenhahn” advocated by Charbonnel & Zahn (2007). The excellent agreement between the Li data of low-mass stars that are more evolved than the RGB bump and our models provides strong support to our own sample, the Li data of the less evolved stars of Luck & Heiter (2007) and Liu et al. (2014). In the first case, the Li abundances are LTE, while in the second case we show the NLTE abundances provided by the authors. We find similarly good agreement for both, better than in Sect. 4.2.1. Although we unfortunately have no stars in common with Liu et al. (2014), we see that the inclusion of NLTE corrections does not affect our global conclusions. In addition to the conclusions derived with our own sample, the Li data of the less evolved stars of Luck & Heiter (2007) confirm the importance of rotation-induced mixing for the evolution of the surface Li abundance already at the MS turnoff and along the Hertzsprung gap.

Additionally, for the low-mass range (below ~2 M☉) thermohaline mixing occurs after the end of the first dredge-up event once the models reach the so-called RGB luminosity bump (which occurs at $T_{\text{eff}} \sim 4400$–4300 K, see Figs. 11 and 12, left panels). This leads to further Li depletion, as thermohaline mixing quickly transports Li from the convective envelope to hotter regions where it efficiently burns. The corresponding transport coefficient is obtained with the prescription for the thermohaline diffusion coefficient “à la Ulrich & Kippenhahn” advocated by Charbonnel & Zahn (2007). The excellent agreement between the Li data of low-mass stars that are more evolved than the RGB bump and our models provides strong support to our prescription for thermohaline mixing, despite existing tension with numerical simulations of this process (e.g., Denissenkov 2010b; Traxler et al. 2011; Sengupta & Garaud 2018). The same coefficient also accounts for the observed behaviour of the carbon isotopic ratio and of the abundances of C and N in the upper part of the RGB in Population I and II stars (Charbonnel & Zahn 2007; Charbonnel & Lagarde 2010; Lagarde et al. 2012), and for the C and N abundances of giant stars investigated in the Gaia-ESO survey (Lagarde et al. 2019). It also leads to a significant reduction of the production of $^3$He in low-mass stars, in better agreement with the behaviour of the evolution of this light element in the Galaxy (Charbonnel & Zahn 2007; Lagarde et al. 2011).

In more massive stars (above ~2 M☉; Figs. 11 and 12, right panels), thermohaline mixing is not expected to occur, because the stars do not pass through the RGB bump as they ignite central He burning earlier in non degenerate conditions. For the upper mass range, the lowest Li abundance observed can simply be explained by higher initial rotation rates, as already discussed above. Again, the above conclusions for the upper part of the RGB (both for the low-mass and the more massive stars) would not be affected by NLTE corrections, since most of the cooler stars have only Li upper limits.

4.2.2. Comparison with Luck & Heiter (2007) and Liu et al. (2014) samples

For the samples of Luck & Heiter (2007) and Liu et al. (2014) we considered only the stars that have both parallaxes and V magnitudes from Gaia DR2 (290 out of 297 stars for Luck & Heiter 2007 and 375 out of 378 for Liu et al. 2014). In this case, we used bolometric corrections from Alonso et al. (1999) to compute the luminosities. The mass (and the error on the mass) of the sample stars were determined as described in Sect. 4.1 and are listed in Table 2.

The predictions of the same rotating models at solar metallicity are compared in Figs. 13 and 14 to the observations of the stars with [Fe/H] between +0.2 and −0.2 (inclusive) of the samples of Luck & Heiter (2007) and Liu et al. (2014). In the first case, the Li abundances are LTE, while in the second case we show the NLTE abundances provided by the authors. We find similarly good agreement for both, better than in Sect. 4.2.1. Although we unfortunately have no stars in common with Liu et al. (2014), we see that the inclusion of NLTE corrections does not affect our global conclusions. In addition to the conclusions derived with our own sample, the Li data of the less evolved stars of Luck & Heiter (2007) confirm the importance of rotation-induced mixing for the evolution of the surface Li abundance already at the MS turnoff and along the Hertzsprung gap.

4.2.3. Comparison to GALAH sample with Gaia DR2 parallaxes

In DR2 of the GALAH survey (Galactic Archaeology with HERMES; Buder et al. 2018), NLTE Li abundances were delivered for 342682 stars, most of them having Gaia DR2 parallaxes. For comparison with stellar evolution models predictions, we considered only GALAH stars with high accuracy or level of confidence in derived stellar parameters and Li abundance (i.e., with FlagCannon = 0 and FlagLi ≤ 1). Gaia DR2 parallaxes with errors less than 20%, and errors on $T_{\text{eff}}$ less than 150 K. These selection criteria yielded a total of 7829 stars (MS and giants). We used bolometric corrections from Alonso et al. (1999) to compute the luminosities. The mass (and the error on the mass) of the sample stars was determined as described in Sect. 4.1. The positions of the stars in the HRD are compared with the standard evolution tracks of Lagarde et al. (2012) in Fig. 10 (we show only the stars with [Fe/H] ≤ +0.2).

For the comparison with model predictions for Li, we focussed on evolved stars ($T_{\text{eff}}$ lower than 5500 K, that is, 1734 stars in total). To test for metallicity effects, we select two subsamples with [Fe/H] between −0.2 and +0.2 (inclusive; 996 stars) on the one hand and [Fe/H] below −0.2 (391 stars) on the other hand. The behaviour of the NLTE Li abundance along evolution is shown in Figs. 15 and 16, with relevant models for different mass ranges. A striking relation becomes apparent between A(Li) and $T_{\text{eff}}$, which is not observed in any of the other samples. Thus, we looked for the differences in the data that could explain this
Some studies use HIPPARCOS or Gaia data to determine the evolutionary status of field LiRG and show that these objects tend to accumulate close to the RGB bump, the clump, and the early-AGB (e.g. Charbonnel & Balachandran 2000; Kumar et al. 2011; Monaco et al. 2011; Lyubimkov et al. 2012; Casey et al. 2016; Smiljanic et al. 2018; Yan et al. 2018; Singh et al. 2019; Deepak 2019).

4.3.2. Li-rich giants in the samples considered in the present study

As mentioned above, the lower Li abundance for a LiRG is usually taken equal to 1.5 dex. This refers to a standard first dredge-up dilution factor of ~60, for a star with an initial cosmic abundance of 3.3 dex. Although this is in principle relevant for Pop I giant stars that have already undergone the first dredge-up, this is not an appropriate criterion for less evolved stars that have not yet undergone full Li dilution. Additionally, more metal-poor stars were probably born with a lower initial Li abundance, with a value of ~2.5 dex for stars with ~3 times fewer metals than the Sun (discussion and references in Sect. 4.2.1). Finally, uncertainties in the actual Li abundances should be taken into account, including those related to NLTE corrections.

4.3. Li-rich stars

4.3.1. Li-rich giants: where do we stand?

Li-rich giants (LiRG) are usually defined as evolved stars with A(Li) higher than 1.5 dex, which is the mean post dredge-up value predicted by standard evolution for Population I stars (see Sect. 4.2.1). They are distinct from AGB stars producing Li through the Cameron & Fowler (1971) mechanism during the thermal pulse phase (e.g. Smith & Lambert 1989; Forestini & Charbonnel 1997; Domínguez et al. 2004). Since the discovery of the first LiRG (Wallerstein & Sneden 1982), several surveys have reported the existence of such objects which account for ~1–2% of the studied populations (Brown et al. 1989; Charbonnel & Balachandran 2000; Reddy & Lambert 2005; Lébre et al. 2006; Gonzalez et al. 2009; Kumar et al. 2011; Monaco et al. 2011; Lyubimkov et al. 2012; Casey et al. 2016; Smiljanic et al. 2018; Yan et al. 2018; Singh et al. 2019; Deepak 2019).

Fig. 17. Colour-coded S/N from Buder et al. (2018) for the GALAH sub-sample selected with the criteria described in the text.
The total percentage for LiRG found in the surveys of the literature. With
\[ A(Li) \geq 0.2 \text{ dex} \]
respectively. This corresponds to 0.5 and 2% of the total number of
samples of Liu et al. (2014) and Luck & Heiter (2007), respective-
ly. conclusion can be obtained on their actual evolution state.

Upon applying our criterion, we find two and six LiRG in the
surveys of Liu et al. (2014) and Luck & Heiter (2007), respec-
tively. This corresponds to 0.5 and 2% of the total number of
red giant stars considered from the respective surveys. We find
no LiRG among our GALAH subsample while Deepak (2019)
found 0.2% LiRG and 0.03% super Li-rich giant (\( A(Li) > 3.0 \text{ dex} \));
all the others have \( A(Li) \leq 2.5 \text{ dex} \). All of them
lie close to the RGB bump and the He-burning clump, except for
two objects that are much brighter and more massive than the rest
of the LiRG subsample, and which have relatively low [Fe/H]. The
position of the low-mass LiRG is, thus, in agreement with the pre-
vious findings. Without asteroseismology however, no definitive

\[
\begin{array}{cccccccc}
\text{HD} & T_{\text{eff}} & e(T_{\text{eff}}) & \log (L/L_\odot) & e(L) & [\text{Fe/H}] & A(Li) & \text{Mass} (M_\odot) & e(M_{\text{eff}}-1\sigma) (M_\odot) \\
3750 & 4610 & 110 & 1.67 & 0.02 & 0.0 & 2.5 & 1.49 & 0.5 \\
4042 & 5020 & 120 & 1.62 & 0.026 & -0.3 & 1.1 & 2.0 & 0.9 \\
30197 & 4490 & 110 & 1.75 & 0.04 & 0.2 & 1.5 & 1.68 & 0.62 \\
40827 & 4620 & 110 & 1.83 & 0.02 & -0.1 & 1.9 & 1.57 & 0.53 \\
71129 & 4460 & 90 & 3.91 & 0.07 & -0.6 & 1.2 & 5.92 & 0.0 \\
77361 & 4600 & 90 & 1.87 & 0.02 & 0.0 & 4.6 & 1.78 & 0.59 \\
83506 & 4810 & 110 & 2.34 & 0.03 & -0.5 & 0.9 & 2.98 & 0.69 \\
85563 & 4530 & 90 & 1.76 & 0.04 & 0.0 & 1.5 & 1.39 & 0.4 \\
86634 & 4650 & 100 & 1.74 & 0.02 & 0.0 & 2.0 & 1.63 & 0.64 \\
90507 & 5030 & 110 & 1.48 & 0.02 & -0.3 & 1.3 & 1.9 & 0.4 \\
90633 & 4580 & 90 & 1.68 & 0.02 & 0.0 & 2.0 & 1.42 & 0.43 \\
93859 & 4590 & 110 & 1.92 & 0.03 & -0.3 & 0.9 & 1.39 & 0.4 \\
106574 & 4490 & 90 & 2.19 & 0.03 & -0.4 & 1.1 & 1.53 & 0.55 \\
113049 & 4810 & 110 & 2.17 & 0.031 & -0.3 & 1.1 & 2.98 & 1.18 \\
115296 & 4630 & 110 & 1.71 & 0.02 & -0.2 & 3.6 & 1.29 & 0.34 \\
133086 & 4890 & 110 & 1.73 & 0.02 & -0.2 & 1.9 & 2.0 & 1.05 \\
138289 & 4460 & 100 & 1.72 & 0.02 & -0.2 & 3.0 & 1.39 & 0.41 \\
183912 & 4680 & 80 & 2.96 & 0.07 & -0.1 & 1.7 & 4.99 & 1.0 \\
188114 & 4810 & 250 & 1.98 & 0.04 & -0.4 & 0.9 & 1.87 & 0.75 \\
199437 & 4560 & 110 & 2.18 & 0.03 & -0.3 & 0.9 & 1.85 & 0.66 \\
206078 & 4940 & 80 & 1.58 & 0.02 & -0.6 & 1.1 & 1.49 & 0.61 \\
\end{array}
\]

It is for these reasons that we identify as LiRG those stars
that have LTE Li abundance and 0.2 dex higher than the Li value
predicted by the standard models at the corresponding effective temperature and for the relevant value of [Fe/H] (see Fig. 11
and related figures). We chose this value of 0.2 dex as it corre-
.png
sponds to the typical uncertainty for the Li abundance. We pro-
vide information on the LiRGs of our own sample and that of
Luck & Heiter (2007) and Liu et al. (2014) in Tables 3 and 4
respectively. The position of all the LiRG we identified is shown
in the HRD in Fig. 18.

In our own sample (Fig. 18 and Table 3) we identify seven
LiRG that pass the “classical” criterion (\( A(Li) \geq 1.5 \text{ dex} \)).
This corresponds to 0.9% of the stars we observed, which a typical percentage for LiRG found in the surveys of the literature. With
our new criterion, we obtain twelve additional LiRG. The total
nineteen stars correspond to 2.2% of our sample. Only two LiRG
have Li higher than the cosmic value of 3.3 dex, one has a Li abun-
dance of 3.0 dex; all the others have \( A(Li) \leq 2.5 \text{ dex} \). All of them
lie close to the RGB bump and the He-burning clump except for
two objects that are much brighter and more massive than the rest
of the LiRG subsample, and which have relatively low [Fe/H]. The
position of the low-mass LiRG is, thus, in agreement with the pre-
vious findings. Without asteroseismology however, no definitive

\[
\begin{array}{cccccccc}
\text{HD} & T_{\text{eff}} & \log (L/L_\odot) & e(L) & [\text{Fe/H}] & A(Li) & \text{Mass} (M_\odot) & e(M_{\text{eff}}-1\sigma) (M_\odot) \\
186815 & 5116 & 1.32 & 0.02 & -0.22 & 1.29 & 1.9 & 0.2 & 0.1 \\
214995 & 4737 & 1.55 & 0.02 & 0.0 & 3.01 & 1.59 & 0.75 & 0.9 \\
5395 & 4774 & 1.75 & 0.03 & -0.45 & 1.3 & 1.39 & 0.54 & 0.5 \\
35410 & 4809 & 1.59 & 0.03 & -0.33 & 1.26 & 1.39 & 0.55 & 0.6 \\
102845 & 4975 & 2.01 & 0.03 & -0.07 & 2.11 & 2.99 & 0.5 & 0.01 \\
138905 & 4822 & 1.85 & 0.03 & -0.3 & 1.44 & 1.79 & 0.79 & 1.19 \\
160781 & 4593 & 2.6 & 0.04 & -0.02 & 1.46 & 3.99 & 1.01 & 1.0 \\
196857 & 4878 & 1.70 & 0.02 & -0.27 & 1.22 & 1.69 & 0.83 & 0.8 \\
\end{array}
\]

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is both brighter and more massive than the bulk LiRG sample. Again, no definitive conclusion can be obtained on their actual evolution state without asteroseismic constraints.

4.3.3. In terms of planets

The entire LiRG sample has been cross-matched with the current sample of 112 published substellar companions around giant stars, a list kept up-to-date by Sabine Reiter's Heidelberg team and no match was found. In order to avoid any error in the determination of the host evolutionary stage, we extended our search to the current sample of 4003 published confirmed exoplanets, once again leading to no match.

5. Conclusions

Li is a fragile element that can be used as a tracer of rotation processes in stellar interiors along the evolution of LIMS. Its photospheric abundance is known to vary extensively with initial stellar mass and evolution stage. Here we test stellar evolution models which predict stronger Li depletion for higher initial rotation in the advanced phases of the evolution as well as a strong impact of thermohaline mixing on low-mass, bright RGB stars. For this purpose, we derived Li abundances in a volume-limited sample of field giant stars with precise Gaia parallaxes and we also used literature samples with HIPPARCOS or Gaia measurements. The model-data comparison confirms the impact of rotation-induced mixing and provides excellent support for our prescription for the efficiency of thermohaline mixing. Finally, we find only 0.8% of LiRG in our sample when using the classical definition used in the literature, and 2.2% when choosing a definition that accounts for the actual evolution stage of the stars with respect to the end of the first dredge-up. We can conclude that Gaia puts a new spin on how the mixing processes in stars are understood. However, asteroseismology is required to definitively pinpoint the actual evolution status of the LiRG.

References

Aguilera-Gómez, C., Chanamé, J., Pinsonneault, M. H., & Carlberg, J. K. 2016a, ApJ, 829, 127
Aguilera-Gómez, C., Chanamé, J., Pinsonneault, M. H., & Carlberg, J. K. 2016b, ApJ, 833, L24
Alexander, J. B. 1967, The Observatory, 87, 238
Alonso, A., Arrasib, S., & Martínez-Roget, C. 1999, A&AS, 140, 261
Alschuler, W. R. 1975, ApJ, 195, 649
Andrae, R., Fouesneau, M., Creevey, O., et al. 2018, A&A, 616, A8
Anthony-Twarog, B. I., Deylanniuss, C. P., Twarog, B. A., Croxall, K. V., & Cummings, J. D. 2009, AJ, 138, 1171
Arenou, F., Luri, X., Babusiaux, C., et al. 2018, A&A, 616, A17
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Balachandran, S. 1990, ApJ, 354, 511
Balachandran, S. 1995, ApJ, 456, 203
Bharat Kumar, Y., Singh, R., Eswar Reddy, B., & Zhao, G. 2018, ApJ, 858, L22
Boesgaard, A. M. 1987, PASP, 99, 1067
Boesgaard, A. M., & Tripicco, M. J. 1986, ApJ, 302, L49
Brown, J. A., Sneden, C., Lambert, D. L., & Dutchover, Jr., E. 1989, ApJS, 71, 293
Buder, S., Asplund, M., Duong, L. et al. 2018, MNRRAS, 478, 4513
Caffau, E., Ludwig, H. G., Steffen, M., & Bonfandczo, P. 2010, in Light Elements in the Universe, eds. C. Charbonnel, M. Tosi, F. Primas, & C. Chiappini, IAU Symp., 268, 329
Cameron, A. G. W., & Fowler, W. A. 1971, ApJ, 164, 111
Carlberg, J. K., Smith, V. V., Cunha, K., Majewski, S. R., & Rood, R. T. 2010, ApJ, 723, L103
Carlos, M., Nissen, P. E., & Meléndez, J. 2016, A&A, 587, A100
Casey, A. R., Ruchti, G., Masseron, T., et al. 2016, MNRRAS, 461, 3336
Casey, A. R., Ho, A. Y. Q., Ness, M., et al. 2019, ApJ, 880, 125
Casissi, S., Salarius, M., & Pietrinferni, A. 2016, A&A, 585, A124
Castro, M., Do Nascimento, Jr., J. D., Biazzo, K., Meléndez, J., & de Medeiros, J. R. 2011, A&A, 526, A17
Charbonnel, C., & Balachandran, S. C. 2000, A&A, 359, 563
Charbonnel, C., & Lagarde, N. 2010, A&A, 522, A10
Charbonnel, C., & Talon, S. 2005, Science, 309, 2189
Charbonnel, C., & Zahn, J. P. 2007, A&A, 467, L15
Chen, Y. Q., Nissen, P. E., Benoni, T., & Zhao, G. 2001, A&A, 371, 943
Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, Res. Astron. Astrophys., 12, 1197
Cummings, J. D., Delyanniuss, C. P., Maderak, R. M., & Steinhauser, A. 2017, AJ, 153, 128
de La Reza, R., Drake, N. A., & da Silva, L. 1996, ApJ, 456, L115
de la Reza, R., da Silva, L., Torres, C. A. O., & Martin, E. L. 1997, ApJ, 482, L77
de Laverny, P., do Nascimento, Jr., J. D., Lèbre, A., & De Medeiros, J. R. 2011, A&A, 526, A17
Deepak, R. B. E. 2019, MNRRAS, 484, 2000
Delgado Mena, E., Israelian, G., González Hernández, J. I., et al. 2014, A&A, 562, A92
Delgado Mena, E., Bertrán de Lis, S., Adibekyan, V. Z., et al. 2015, A&A, 576, A69
Delgado Mena, E., Tsantaki, M., Sousa, S. G., et al. 2016, A&A, 587, A66
Delianniuss, C. P., Pinsonneault, M. H., & Charbonnel, C. 2000, in The Light Elements and their Evolution, eds. L. da Silva, R. de Medeiros, & M. Spite, IAU Symp., 198, 61
Denissenkov, P. A. 2010a, ApJ, 719, 28
Denissenkov, P. A. 2010b, ApJ, 723, 563
Denissenkov, P. A., & Herwig, F. 2004, ApJ, 612, 1081
Denissenkov, P. A., & Weiss, A. 2000, A&A, 358, L49
Denissenkov, P. A., Pinsonneault, M., & MacGregor, K. B. 2009, ApJ, 696, 1823
Domínguez, I., Abia, C., Straniero, O., Cristallo, S., & Pavlenko, Y. V. 2004, A&A, 422, 1045

Fig. 18. Position in HRD of the LiRG identified with our adopted criterion. Red and blue stars are for Li values higher or lower than 1.5 dex, respectively.
