Letter to the Editor

The behaviour of lithium at high metallicity in the Milky Way
Selection effects in the samples and the possible role of atomic diffusion

C. Charbonnel¹,², S. Borisov¹,³, P. de Laverny⁴, and N. Prantzos⁵

1 Department of Astronomy, University of Geneva, Chemin Pegasi 51, 1290 Versoix, Switzerland
e-mail: Corinne.Charbonnel@unige.ch
2 IRAP, CNRS UMR 5277 & Université de Toulouse, 14 Avenue Edouard Belin, 31400 Toulouse, France
3 Sternberg Astronomical Institute, M.V. Lomonosov Moscow State University, Universitetskyy Prospect 13, Moscow 119234, Russia
4 Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, Nice, France
5 Institut d’Astrophysique de Paris, UMR 7095 CNRS, Sorbonne Université, 98bis Bd. Arago, 75104 Paris, France

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ABSTRACT

Aims. We revisit large spectroscopic data sets for field stars from the literature to derive the upper Li envelope in the high metallicity regime in our Galaxy.

Methods. We take advantage of Gaia EDR3 data and state-of-the-art stellar models to precisely determine the position of the sample dwarf stars in the Hertzsprung-Russell diagram.

Results. The highest Li abundances are found in field metal-rich warm dwarfs from the GALAH survey, located on the hot side of the Li-dip. Their mean Li value agrees with what was recently derived for warm dwarfs in metal-rich clusters, pointing towards a continuous increase of Li up to super-solar metallicity. However, if only cool dwarfs are considered in GALAH, as done in the other literature surveys, it is suggested that the upper Li envelope decreases at super-solar metallicities, blurring the actual Li evolution picture. We confirm the suggestion that field and open cluster surveys that found opposite Li behaviour in the high metallicity regime do not sample the same types of stars: The first ones, with the exception of GALAH, miss warm dwarfs that can potentially preserve their original Li content.

Conclusions. Although we can discard the bending of the Li upper envelope at high metallicity derived from the analysis of cool star samples, we still need to evaluate the effects of atomic diffusion on warm, metal-rich early-F and late-A type dwarfs before deriving the actual Li abundance at high metallicity.

Key words. stars: abundances – Galaxy: abundances – Galaxy: evolution

1. Introduction

Lithium-7 (Li) is the only element that has been produced in three extremely different astrophysical sites: in the very early universe during the Big Bang nucleosynthesis episode, in interstellar matter through cosmic ray spallation reactions and, mostly, in stars of still undetermined type (red giants, asymptotic giant branch stars, novae, and core collapse supernovae: Matteucci et al. 1995; Travaglio et al. 2001; Romano et al. 2001; Prantzos 2012). Quantitative predictions of Li evolution in different regions of the Milky Way hence remain challenging. It is generally expected, however, that the Galactic Li content is globally increasing with time (or metallicity), with variations depending on the regions considered (thin and thick discs, the bulge, and halo). This view is well supported by the observed upper envelope of Li abundances in low-mass stars (LMS) as a function of [Fe/H], which increases up to solar metallicity (e.g. Rebolo et al. 1988; Bensby & Lind 2018).

It thus came as a surprise when high-resolution spectroscopic data sets such as AMBRE (de Laverny et al. 2013; Guiglion et al. 2016) and others (Delgado Mena et al. 2015; Fu et al. 2018; Bensby et al. 2020; Stonkutė et al. 2020) focusing on cool field main sequence (MS) stars indicated that Li may be decreasing at super-solar metallicities. If this finding were confirmed, it would be the first time that an element other than H displays a decrease with metallicity (Prantzos et al. 2017). A few ideas were put forward to cope with this unprecedented situation (Fu et al. 2018; Guiglion et al. 2019; Grisoni et al. 2019), although Prantzos et al. (2017) had warned that the results deduced from AMBRE would require further analysis and additional observations before establishing such far reaching conclusions. This finding has indeed been challenged recently, by observations of warm MS stars in metal-rich open clusters (Gaia-ESO survey, Randich et al. 2020) and in the field (GALAH survey, Gao et al. 2020), which show high Li abundances above the meteoritic value, in line with Galactic chemical evolution expectations.

One difficulty to determine the upper Li envelope as a function of metallicity as required to constrain Galactic chemical evolution models is that stars rarely exhibit in their photosphere the Li content they inherited from their protostellar cloud. This is due to the fragility of this light element, which is destroyed by proton captures at \( \sim 2.5 \, \text{MK} \) in stellar interiors. There is plentiful observational evidence of surface Li depletion in FGK dwarfs along their early evolution, starting with the Sun whose photospheric Li abundance is \( \sim 195 \) times lower than in meteorites...
2. Looking for stars that might preserve their original surface Li

Drawing the upper Li envelope as a function of [Fe/H] requires finding stars that exhibit Li abundances as close as possible to their original composition. Pre-main sequence (PMS) stars could be thought of as the best targets. However, observations in star forming regions, moving groups and associations, and very young open clusters have shown that PMS stars could be thought of as the best targets. However, observations in star forming regions, moving groups and associations, and very young open clusters have shown that PMS stars with masses lower than \( \sim 0.9 M_\odot \) (at solar metallicity), or early-F type MS stars with effective temperatures higher than \( \sim 6800 \) K (i.e., masses higher than \( \sim 1.5 M_\odot \) at solar metallicity) and with relatively high rotation rates to counteract atomic diffusion. Such objects will be absent in the metal-poor regime where the age of the sampled populations is larger than the duration of the PMS or the MS lifetime of early-F type stars (\( \sim 1.8 \) to 2.9 Gyr for \( 1.5 M_\odot \) models presented in this work with [Fe/H] between –0.23 and +0.5). Additionally, both groups of stars can be easily missed, especially if volume-limited (stellar) samples with completeness and selection function often difficult to estimate accurately. Technically, the Li resonance line at 6708 Å becomes weaker and weaker with an increasing effective temperature, requiring high signal-to-noise spectra and optimised normalisation procedures. Moreover, relatively high rotation rates broaden the lines and lead them to be even closer to the continuum level. Such cases are thus more difficult to treat by automatic procedures.

3. Looking for PMS and early-F type stars in field star surveys at solar metallicity and above

3.1. Selection criteria

We revisit the samples where a decline in the upper Li envelope at solar metallicity has been found, putting more emphasis on AMBRE (de Laverny et al. 2013; Guiglion et al. 2016) and briefly discussing the others (Delgado Mena et al. 2015; Fu et al. 2018; Bensby et al. 2020; Stonkutė et al. 2020). We also investigate the new release of the GALAH survey (Buder et al. 2020; Gao et al. 2020). In all cases we focus on the domain in [Fe/H] between –0.2 and +0.4 dex that we split into four bins of 0.15 dex. Bin 1 is sub-solar (\(-0.20 < [\text{Fe/H}] < -0.05\) dex), bin 2 is centred on solar metallicity (\(-0.05 < [\text{Fe/H}] < +0.10\) dex), and bins 3 and 4 are for the super-solar regimes (\(+0.10 < [\text{Fe/H}] < +0.25\) and \(+0.25 < [\text{Fe/H}] \leq +0.40\) dex, respectively).

We relied on the stellar parameters and abundances published in the original papers (\( T_{\text{eff}}, \log g, [\text{Fe/H}], \) and \( \text{A}(\text{Li})_{\text{LTE}} \) and kept only stars with \( \log g \geq 4 \)). Since the GALAH data contain lithium abundance as \([\text{Li}/\text{Fe}]\), we adopted \( \text{A}(\text{Li}) = [\text{Fe/H}] + [\text{Li}/\text{Fe}] + \text{A}(\text{Li})_{\odot} \) with \( \text{A}(\text{Li})_{\odot} = 0.96 \) dex (Wang et al. 2021). We applied non-local thermodynamic equilibrium (NLTE) corrections according to Wang et al. (2021) to the published AMBRE LTE Li abundances; this NLTE correction was already applied in the GALAH sample. We applied the quality criteria provided in the reference papers to select the stars with the most reliable abundances and stellar parameters. In GALAH, we selected only stars with \( \text{FLAG}\_\text{LI} \_\text{Fe} = 0 \) (quality flag on \([\text{Li}/\text{Fe}]\), see Buder et al. 2020 for details), \( \text{FLAG}\_\text{SP} = 0 \) (stellar parameters quality flag), and S/N per pixel \( \geq 30 \).

We kept only those stars with Gaia EDR3 parallax uncertainties lower than 5% and RUWE \( < 1.4 \). We used G-band photometry from Gaia EDR3 and distances \( d \) from Bauer-Jones et al. (2021, excluding possible less-quality parallaxes thanks to the
RUWE parameter) to determine the luminosity $L$ of the sample stars, defined as $L = 10^{(0.4 M) \cdot (G + 5 \cdot \log \Delta V + \text{BCG} - A_G)}$ in units of $L_\odot$, where $M = 1.947$ (IAU resolution 2015, Prša et al. 2016). The bolometric correction BCG was computed according to Andrae et al. (2018) adopting the effective temperatures provided by the ground-based surveys. The $A_G$ is the G-band extinction from Gaia DR2, which is consistent with the DR2 colours adopted for deriving DR2 BCG and $T_{\text{eff}}$. Error on luminosity (typically ~10%) is dominated by the one on $A_G$ (typically ~0.11 mag), which is small enough to not affect our conclusions. Finally, since a degeneracy could exist between the Gaia DR2 derived $T_{\text{eff}}$ and extinction, we kept only stars having consistent effective temperatures: $|T_{\text{Gaia}} - T_{\text{GALAH}}| \leq 200$ K. With these selection criteria, for $[\text{Fe/H}] > -0.2$ dex, we have 962 stars in AMBRE, and 21,130 stars in GALAH.

To distinguish PMS stars, we made a cross-match of the samples with the SIMBAD database (Wenger et al. 2000). We looked for stars of the following types: T Tauri star, young stellar object, and “variable star of Orion type”. As can be seen from Fig. 1, the GALAH sample does not contain PMS stars, in contrast to the AMBRE sample. This is because we selected only stars being flagged by GALAH with flag_sp = 64 refers to both binary and PMS stars.

3.2. Positions of the sample stars in the HRD and determination of the Li upper envelope

Figure 1 shows the position of individual stars in the four metallicity bins for AMBRE and GALAH samples, respectively. NLTE Li abundances are colour-coded, and the seven Li richest stars in each individual metallicity bin are highlighted, as well as the known PMS stars. PMS and MS evolutionary tracks from Lagarde et al. (2017) completed by tracks at $[\text{Fe/H}] = +0.25$ computed with the same code and input physics are also shown.

We immediately see that there are no late-A and early-F type metal-rich dwarf star with $T_{\text{eff}} > 6800$ K in the AMBRE sample (see also Fig. 3 of Guiglion et al. 2016), and that in the most metal-rich bin the seven Li-richest stars are cool stars lying close to other stars which show very strong Li depletion. The lack of warm stars is inherent to the AMBRE/Li catalogue. First, the AMBRE sample consists in a wealth of ESO archived spectra that have been collected for various scientific goals. Moreover, within AMBRE, the stars are parametrised thanks to automated pipelines that rely on pre-computed grids of non-rotating FGKM-type stellar spectra. Such a methodology thus a priori rejects non-rotating stars hotter than ~7500 K and any cooler ones having rotation rates larger than ~15 km s$^{-1}$ (Worley et al. 2012), leading to a final sample biased towards cool and slowly rotating stars. We did the same analysis for the samples of Delgado Mena et al. (2018), Fu et al. (2018), and Strokute et al. (2020). As in AMBRE, none of the sample stars used for the derivation of the Li upper envelope in the high metallicity regime lie on the hot side of the Li dip.

In contrast, early-F and late-A type stars with $T_{\text{eff}} > 6800$ K are present in the four metallicity bins of the GALAH sample (Fig. 1), and they always exhibit the highest Li abundances in the respective bins, which is in agreement with what is found in open clusters. The average Li value we get for the seven Li-richest stars in this $T_{\text{eff}}$ domain for the highest metallicity bin is 3.28 dex, with the Li richest star having 3.46 dex. As can be seen in Fig. 2, this agrees perfectly with the average maximum A(Li) values for the supersolar metallicity open clusters by Randich et al. (2020) for which the authors selected upper MS stars on the warm side of the Li dip (above 6500 K actually). Their Li abundances were not corrected for NLTE effects, but the authors argue that these corrections should be significantly lower than +0.1 dex. The A(Li) trend with $[\text{Fe/H}]$ they obtain is in very good agreement with the one we derived when we used the similarly Li-rich stars from the hot side of the dip in the GALAH sample.

Finally, we also show in Fig. 2 the average Li value of the seven most Li-rich stars of GALAH in the reduced cool $T_{\text{eff}}$
4. Toward a reliable conclusion on the Li trend in the high metallicity regime

Since we are mostly interested in the metal-rich regime, we focus our discussion on the seven Li-richest stars of GALAH bin 4 (+0.25 < [Fe/H] < +0.4) that have a $T_{\text{eff}}$ between 6960 and 7650 K. As already mentioned, deriving abundances in warm, possibly fast rotating, dwarf stars, is challenging. However, we consider only stars with high resolution, high S/N spectra; the S/N per resolution element range is between 122 and 965 for these seven Li-rich stars. Additionally, they are relatively slow rotators for their spectral types ($v \sin i$ between 16 and 52 km s$^{-1}$ according to GALAH DR3), and they are supposedly single stars (flag_sp = 0). Specific tests based on simulated spectra of such rotating stars confirmed that the derived Li abundances are reliable for the considered high S/Ns.

On the other hand, stars with a $T_{\text{eff}}$ higher than ~6800 K may show superficial abundance anomalies due to atomic diffusion under the competitive action of gravitational settling and radiative acceleration, unless meridional circulation, turbulence, mass loss, or a combination of these processes partially compensate or eventually erase chemical separation effects (e.g., Michaud et al. 1983; Vauclair & Vauclair 1982; Turcotte et al. 1998). The actual rotation threshold between normal A-type stars and chemically peculiar Am ones is, however, not firmly established observationally or theoretically (it varies in the literature between ~60 and 120 km s$^{-1}$), with also binarity playing a possible role (Abt & Willmarch 2000; Varenne & Monier 1999; Royer et al. 2014).

We thus looked for possible signatures of chemical separation in the seven Li-richest stars of GALAH bin 4, using DR3 abundances (Buder et al. 2020). We checked particular elements that are expected to be overabundant (Ti, Cr, Mn, Fe, Ni, and Ba) and others that are expected to be underabundant (Li, O, Mg, Si, K, and Ca) in AmFm-type stars (Preston 1974; Richard et al. 2001; Talon et al. 2006; Vick et al. 2010) compared to normal A-type stars (Bill & Landstreet 1993; Varenne & Monier 1999; Adelman et al. 2000). The corresponding [X/H] values are shown in Fig. 3, together with those of other elements that should not be significantly affected by atomic diffusion in these warm stars (Na, Al, and Sc). For each element, we also show the observed abundance range in G-type stars of bin 4, which exhibits important star-to-star abundance variations. Since the surface abundances of these cool stars are not affected by atomic diffusion, this reflects their initial chemical composition (except for Li, which is depleted, as is expected and described in Sect. 2), hence the expected range of abundances that bin 4 stars could have inherited at birth.

Importantly, for most of the elements, the dispersion in abundances among the seven Li-rich stars is in good agreement with (and, for some elements, lower than) the spread in initial abundances depicted by G-type stars. The only elements for which the seven stars deviate from the bulk are Ca, Cu, and Ba, with one star also showing a slight underabundance in C. The Ba overabundances observed in five of the seven stars are, however, lower than the minimum value assumed by Xiang et al. (2020) to characterise metal-rich AmFm stars; additionally, for this element, NLTE effects could potentially be important (Mashonkina et al. 2020) and may blur the comparison with the abundances derived for cool stars. This analysis thus tends to indicate that the seven Li rich stars in GALAH bin 4 have relatively normal abundances of heavy elements.

The actual status (AF versus AmFm) of the warm metal-rich and Li-rich stars however deserves confirmation. Taylor-made
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