LETTER TO THE EDITOR

The *Gaia*-ESO Survey: Galactic evolution of lithium at high metallicity[*]

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ABSTRACT

Context. Reconstructing the Galactic evolution of lithium (Li) is the main tool used to constrain the source(s) of Li enrichment in the Galaxy. Recent results have suggested a decline in Li at supersolar metallicities, which may indicate reduced production.
Aims. We exploit the unique characteristics of the *Gaia*-ESO Survey open star cluster sample to further investigate this issue and to better constrain the evolution of Li at high metallicity.
Methods. We trace the upper envelope of Li abundance versus metallicity evolution using 18 clusters and considering members that should not have suffered any Li depletion.
Results. At variance with previous claims, we do not find any evidence of a Li decrease at high metallicity. The most metal-rich clusters in the sample ([Fe/H] = ~0.3) actually show the highest Li abundances, with A(Li) > 3.4. Our results clearly show that previous findings, which were based on field stars, were affected by selection effects. The metal-rich population in the solar neighbourhood is composed of relatively old and cool stars that have already undergone some Li depletion; hence, their measured Li does not represent the initial interstellar medium abundance, but a lower limit to it.

Key words. stars: abundances – Galaxy: abundances – Galaxy: evolution – open clusters and associations: general

1. Introduction

Trimble & Leonard (1994) summarised very effectively the relevance of lithium (Li) in modern astrophysics: "We continue to find it slightly disconcerting that so uncommon an element as lithium should be so important for studying the structure of outer layers of stars, not to mention the early Universe. But so it is". If we were able to fully understand and model Li observations in stars and in the interstellar medium (ISM), we would also be able to answer a number of interesting astrophysical questions.

In particular, focusing on the Galactic evolution of Li abundance and its trend with metallicity, numerous papers have been published since one of the first studies (Rebolo et al. 1988); nevertheless, a major question remains open; namely, what

Li production sources contribute to the Li enrichment in the Galaxy and can explain the increase from the plateau value (Spite & Spite 1982) observed in metal-poor Population II stars to the factor of ~10 higher Li measured in meteorites and young T Tauri stars (see e.g. D'Antona & Matteucci 1991; Travaglio et al. 2001; Cescutti & Molaro 2019)[1].

Whilst it is not easy to summarise and review all the works that have addressed Li abundances and Galactic Li evolution in the past thirty years, a few recent observational results can be highlighted. In particular, we note that amongst the proposed contributors to the Li enrichment in the Galaxy, asymptotic giant branch (AGB) stars ejecta, red giants, supernovae, cosmic ray spallation, and novae, recent observations of novae have clearly

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[1] The plateau Li abundance is a factor of about three smaller than the Big Bang abundance (e.g. Cyburt et al. 2016; Pitrou et al. 2018); hence, Galactic evolution may actually only need to explain the increase from the Big Bang value to the meteoritic value.

detected the lines ^{7}Li or ^{7}Be (which then decays into ^{7}Li) at the early stages, showing that these systems may represent a dominant source of Li enrichment in the Galaxy (Izzo et al. 2015, 2018; Tajitsu et al. 2015; Molaro et al. 2016). Along similar lines, recent observations of large samples of giants provide some support to the idea that these stars may also contribute to the Galactic Li enrichment (e.g. Deepak & Reddy 2020, and references therein), as suggested in Romano et al. (2001). Importantly, the empirical evolution of Li with metallicity has been better constrained thanks to the numerous observations and spectroscopic surveys carried out in recent years, and have indeed produced an astonishing amount of optical high-resolution spectra that allow us to study chemical abundances in the different populations of the Galaxy, investigating simultaneously the evolution of several elements.

Lithium is a fragile element that is destroyed at the relatively low temperature of 2.5×10^6 K in stellar interiors, and may hence be depleted in stellar atmospheres (see e.g. Pinsonneault 1997). Therefore, when looking at the Li versus [Fe/H] distribution, at each metallicity a large dispersion in abundances is observed due to stars that have suffered different amounts of depletion; in order to correctly define the evolution of the original ISM Li abundance with [Fe/H], it is necessary to make sure that the upper envelope of the distribution is traced by undepleted stars whose Li content should be representative of the pristine value. Based on the observed distribution of Milky Way (MW) field stars in the solar vicinity, several recent studies have suggested that this upper envelope declines at supersolar metallicities (Delgado Mena et al. 2015; Guiglion et al. 2016, 2019; Fu et al. 2018; Bensby et al. 2020; Stonkutė et al. 2020). This unexpected result is quite difficult to explain and to model (Grisoni et al. 2019), and alternative explanations have been proposed. On the one hand, it has been suggested that the decrease in Li is due to reduced production in the metal-rich regime (Prantzos et al. 2017; Fu et al. 2018; Grisoni et al. 2019), for example because of lower AGB yields and/or a lower occurrence of nova systems at high metallicity. Alternatively, it has been proposed that the decline in Li is not real, but rather due to the adopted selection functions of the MW field samples. In particular, Anthony-Twarog et al. (2018) point out how the results of Fu et al. might be affected by selection biases and suggest that the maximum Li abundance might actually increase at high metallicity (see also Cummings et al. 2012). Along similar lines, Guiglion et al. (2019) and Bensby & Lind (2018) speculate that metal-rich field stars in the solar vicinity are old stars that have migrated from the inner part of the disc, depleting lithium as they travelled and got older. In other words, Li in those stars may not be representative of the original ISM value.

Clearly, Li measurements in young and metal-rich populations, which have presumably not depleted any Li, and the comparison with their more metal-poor counterparts is crucial to discriminating between the two hypotheses. In this context we exploit the observations of open clusters (OCs) performed by the *Gaia*-ESO Spectroscopic Survey (GES, Gilmore et al. 2012; Randich et al. 2013); in particular, the GES OC sample includes several clusters with supersolar metallicity located in the inner Galaxy that are particularly suited to the above purpose.

2. Sample and lithium determination

Our study is based on the fifth internal data release of the GES (GESiDR5[2]). Spectra for cluster stars were obtained with

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[2] The GESiDR5 catalogue is available for the members of the GES consortium at http://ges.roe.ac.uk/

FLAMES (Pasquini et al. 2002), either with UVES and the 580 setup or with GIRAFFE and the HR15N setup. Both setups include the Li I 6707.8 Å absorption doublet.

Lithium abundances in GESiDR5 were derived by different analysis nodes within dedicated working groups groups (WG10, WG11, WG12; see e.g. Randich et al. 2018 for a detailed description of GES working group data flow and data products). More specifically, one-dimensional (1D), local thermodynamical equilibrium (LTE) abundances $(A(\text{Li}) - \log N(\text{Li})/N(\text{H}) + 12)$ were computed by different nodes adopting GES recommended stellar parameters and considering the Li 6707.8 Å feature, either fitting it with spectral synthesis or by measuring the equivalent width of the line, which was then converted to abundances using a new set of curves of growth specifically derived for GES (Franciosini et al., in prep.). When the Li line was blended with the nearby 6707.4 Å Fe I line, before computing Li abundances the equivalent widths were corrected for the Fe contribution by using the same grid of synthetic spectra used to derive the curves of growth. The abundances from the different nodes were then combined within each working group and then homogenised to produce the final recommended values (Hourihane et al., in prep.).

The sample clusters were chosen starting from the list of OCs analysed in GESiDR5. We selected mainly young or very young clusters, where at least 4−5 members with supposedly pristine unprocessed Li, representative of the ISM value, are present. Specifically, the sample includes the following: i. very young (age < 100 Myr) clusters whose members are pre-main sequence (PMS) or zero age main sequence stars that should have not yet depleted any Li; ii. clusters older than 100 Myr, but generally younger than 2 Gyr, whose upper main sequence (MS) stars are located on the blue (or warm) side of the so-called Li dip (see e.g. Boesgaard & Tripicco 1986; Soderblom et al. 1993a,b; François et al. 2013; Cummings et al. 2017); no Li depletion is expected for these stars (see e.g. Gao et al. 2020) and hence their Li abundance should be representative of the ISM value. The only exceptions to these criteria are NGC 2516, NGC 2420, and NGC 2243. The first cluster is slightly older than 100 Myr, but its members on the blue side of the dip are too bright and were not observed by GES. In the other two clusters, given their ages, stars on the blue side of the dip are no longer on the MS, but are located at the upper turnoff (TO), and they may already have undergone some post-MS Li dilution. Hence the maximum Li that we report for these three clusters is possibly a lower limit to the original ISM value. We decided to retain them as part of the sample in order to enlarge the number of comparison solar-metallicity and metal-poor objects. We also note that some PMS Li depletion may be expected in cool young cluster members due to rotational mixing (see e.g. Bouvier et al. 2016); however, our average maximum Li abundance for these young clusters is based on stars on the upper envelope of the Li versus effective temperature (T_{eff}) distributions, and we can safely assume that the clusters are sampled well enough that the highest Li stars provide the best approximation to their initial Li. The final sample includes 18 OCs, covering the age range between 2 Myr and 5 Gyr; their metallicity (as homogeneously computed by the GES) ranges between [Fe/H] = −0.38 ± 0.04 (NGC 2243) and [Fe/H] = +0.26 ± 0.06 (Ruprecht 134).

Cluster membership was obtained following Jackson et al. (2020) and stars with membership probability higher than 80% were considered. In order to compute the average value of the maximum Li abundance for each cluster, as mentioned, we considered PMS stars in the very young clusters and stars on the blue side of the dip in the older ones. In NGC 2516 the stars with

Table 1. Sample clusters, their parameters, and average maximum Li abundance.

Cluster	Age (Gyr)	R_{GC} (kpc)	[Fe/H]	$A(Li)_{max}$	N stars used	T_{eff} range (K)
NGC 6530	0.002	6.76	-0.041 ± 0.009	3.38 ± 0.06	8	4490–5300
Trumpler 14	0.002	7.62	-0.03 ± 0.016	3.45 ± 0.07	62	4200–5150
Chamaeleon I	0.002	8.0	-0.07 ± 0.017	3.25 ± 0.11	23	3475–4310
ρ Oph	0.003	8.0	-0.08 ± 0.006	3.34 ± 0.14	13	3390–4630
NGC 2264	0.003	8.71	-0.06 ± 0.04	3.31 ± 0.07	12	4032–5154
IC 4665	0.028	7.65	0.00 ± 0.02	3.32 ± 0.16	12	5240–6250
IC 2602	0.03	7.95	-0.02 ± 0.10	3.29 ± 0.18	10	5290–6705
NGC 2547	0.035	8.04	-0.006 ± 0.009	3.27 ± 0.14	21	5615–6930
NGC 6067	0.10	6.81	0.20 ± 0.08	3.41 ± 0.13	4	6630–7370
NGC 2516	0.11	7.98	-0.06 ± 0.05	3.20 ± 0.07	5	6580–6950
NGC 6259	0.21	7.03	0.21 ± 0.04	3.40 ± 0.06	4	6600–7050
NGC 6705	0.30	6.33	0.16 ± 0.04	3.43 ± 0.12	10	7050–7470
Berkeley 81	1	5.49	0.22 ± 0.07	3.45 ± 0.15	11	6490–7480
NGC 6802	1.00	6.96	0.10 ± 0.02	3.36 ± 0.14	5	6760–7230
Ruprecht 134	1.00	4.60	0.26 ± 0.06	3.42 ± 0.10	11	6500–6990
Trumpler 20	1.4	6.86	0.15 ± 0.07	3.38 ± 0.13	4	7025–7170
NGC 2420	2.20	10.76	-0.13 ± 0.04	3.05 ± 0.07	21	6290–6550 (upper TO)
NGC 2243	4.9	10.4	-0.38 ± 0.04	2.96 ± 0.06	5	5890–6190 (upper TO)

Notes. Ages and metallicities were taken from Spina et al. (2017), Magrini et al. (2017), Randich et al. (2018), Casali et al. (2019). The error bars represent the standard deviation of the stars that contribute to the calculation of the mean. The actual error in the mean is a factor of $\sqrt{N}$ smaller.

the highest Li on the red side of the dip were used. Only stars with Li detections (i.e. no upper or lower limits) were taken into account. The results on the maximum Li are given in Table 1, along with the associated dispersion.

3. Results and discussion

Figure 1 summarises our results for the evolution of Li as a function of metallicity. The figure clearly suggests, at variance with previous claims, that the maximum Li abundance does not decrease at high metallicities, at least up to about [Fe/H] ~ +0.3. Actually, the two clusters with subsolar metallicities show a maximum Li abundance below $A(Li) = 3.1$ (but, as mentioned, stars in these clusters may have already suffered some Li dilution), while all the others are above or close to 3.3, and the two most metal-rich (Ruprecht 134 and Berkeley 81) have $A(Li)_{max} \sim 3.4$, which is also much higher than the Li abundances measured in field stars at similar metallicities. Therefore, the main conclusion of this study is that we do not see any evidence of a decrease in Li at supersolar metallicity. Rather, the opposite might be true, and the data may suggest a positive Li versus [Fe/H] trend, in agreement with the suggestions of Anthony-Twarog et al. (2018). Whilst a Bayesian analysis also supports a positive Li versus Fe correlation, this needs to be confirmed with a larger number of clusters, in particular young ones in the metal-poor regime.

Similarly, the data would suggest a mild trend with Galactocentric distance (R_{GC}, see Fig. 2) or a shallow gradient. To our knowledge this is the first time that a Li gradient has been shown observationally; however, also in this case, a larger cluster sample is needed to derive firm conclusions and to perform a comparison with the models.

Given that several recent studies have claimed Li decrease at high metallicity, the opposite of our results, we investigate possible reasons for the disagreement in the following.

3.1. Three-dimensional and non-LTE corrections

Lithium abundances from GES have been computed using LTE and plane-parallel atmospheres, while a more detailed analysis would require considering three-dimensional (3D) models and non-LTE effects (NLTE, e.g. Lind et al. 2009; Klevas et al. 2016; Harutyunyan et al. 2018). Guiglion et al. (2016) and Fu et al. (2018) both applied NLTE corrections using Lind et al. (2009) computations, still with 1D models. Unfortunately, we cannot derive star-by-star NLTE abundances for the whole sample since a detailed grid of NLTE + 3D corrections covering the parameter space of our sample stars is not available in the literature. However, we used the tool provided by Harutyunyan et al. (2018)[3] to estimate the effect of NLTE + 3D corrections. Specifically, we fixed the value of the Li abundance ($A(Li) = 2.7$ – the maximum available in their grid), and changed the star temperature and metallicity. As already described in the original paper, the corrections decrease with increasing effective temperature and, for a fixed temperature (e.g. 6500 K), they slightly increase for higher metallicity. More importantly, the corrections are positive (i.e. by applying 3D+NLTE corrections higher Li abundances are obtained). For example, at solar metallicity we have $A(Li)_{3D-NLTE} - A(Li)_{1D-LTE} = \Delta A(Li) = 0.055$ and 0.024 dex for $T_{eff} = 6000$ and 6500 K, respectively; at [Fe/H] = 0.3 we have $\Delta A(Li) = 0.076$ and 0.038 for the same effective temperatures. For a given effective temperature the dependence of the corrections on $A(Li)$ is negligible. Since the members of the metal-rich clusters used to infer the maximum Li abundance are all warmer than 6500 K, we conclude that the NLTE-corrections should be well below 0.1 dex, and of positive sign. Neglecting NLTE effects is thus not at the root of the discrepancy between our results for the open clusters and the field stars from other studies.

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[3] https://pages.aip.de/li67nlte3d
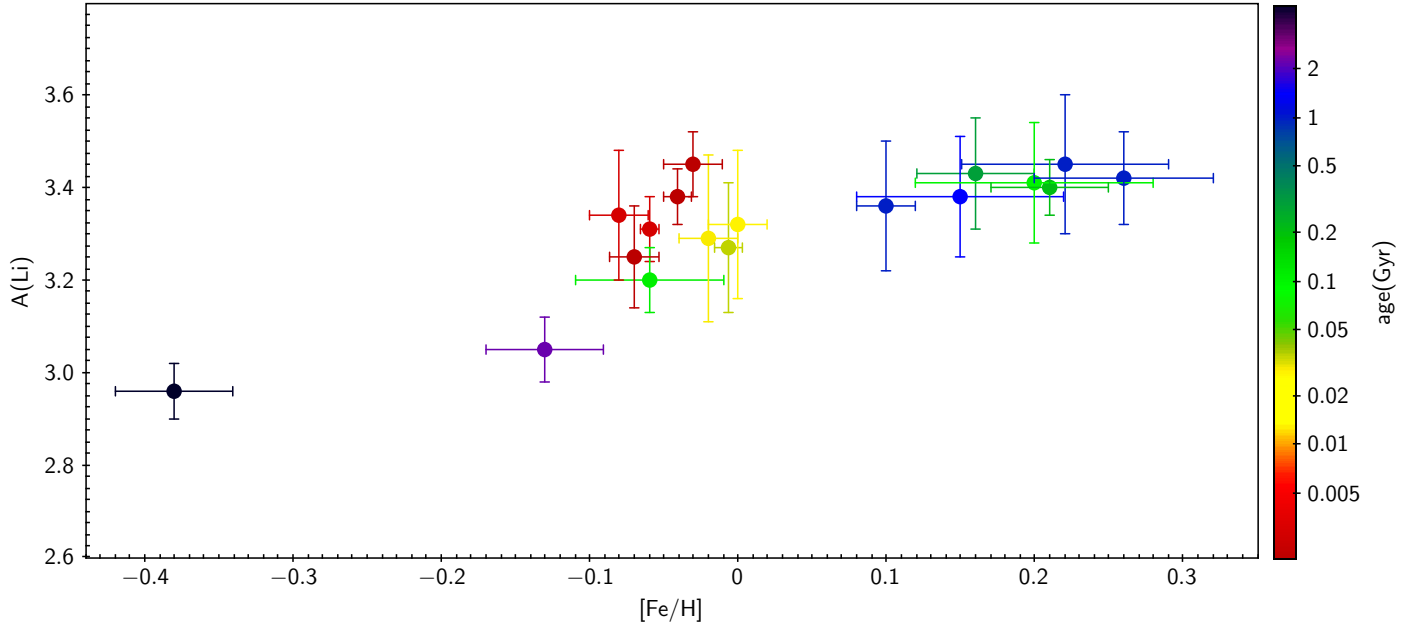
Fig. 1. Average maximum Li abundance (see text) as a function of the cluster metallicity. Clusters are colour-coded by age.
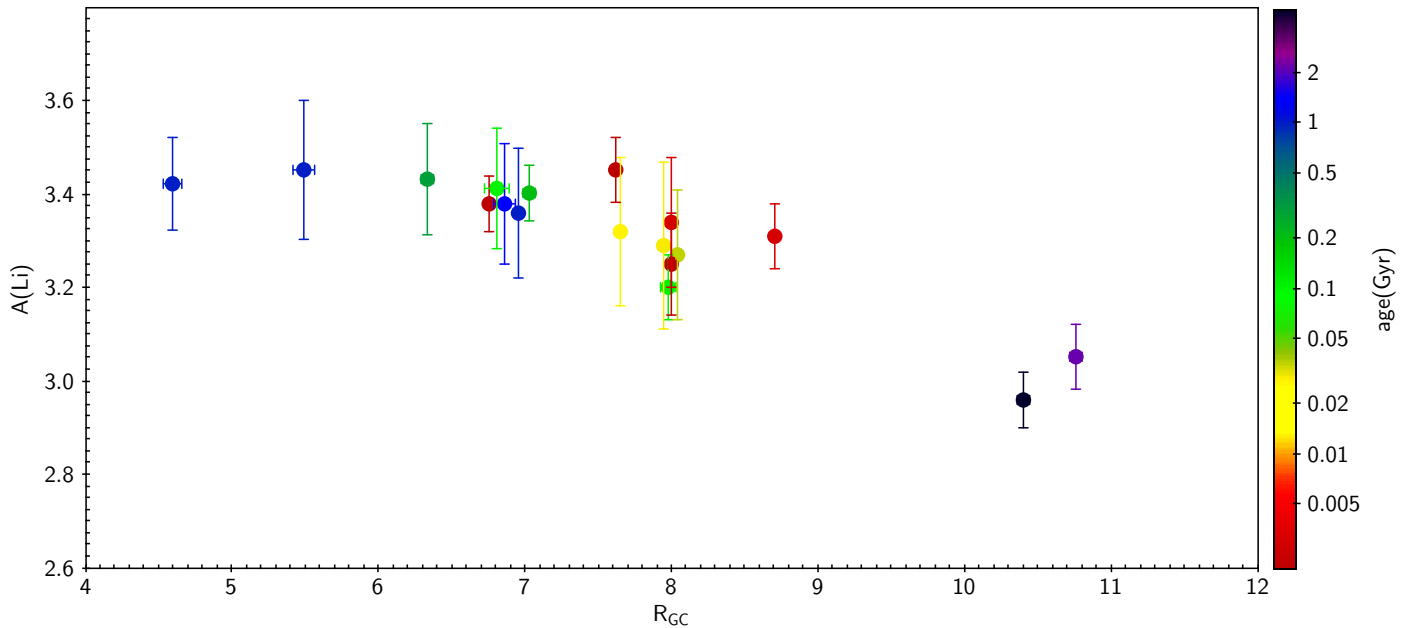

Fig. 2. Same as Fig. 1, but lithium is plotted as a function of the cluster Galactocentric distance.

3.2. Sampling different populations

Most spectroscopic surveys of MW field stars are affected by selection criteria, such as the star's distance (limiting magnitude) or colour selection, that may introduce hidden biases. Observing OCs allows us to eliminate these biases because they are selected based on their combinations of age and metallicity, irrespective of their distance. In addition, since the stars are members of the clusters, we are able to know exactly their evolutionary status and physical parameters, and to cover a wide range of evolutionary stages and masses. In our case we have the additional advantage that the Li dip in many clusters is well defined, so we can use it to guide our analysis. When looking at the main differences between cluster and the field samples observed in spectroscopic surveys, two aspects are important. First, the samples of field

stars (see e.g. Guiglion et al. 2016; Fu et al. 2018) contain in the high-metallicity bin only MS stars with effective temperatures below ~6400 K (i.e. stars located on the cool side of the Li dip). The highest Li values in our sample are instead found amongst stars on the hot side of the dip. This is clearly seen in Fig. 3, where we compare Ruprecht 134 with the GES MW stars with available Li measurements. The Ruprecht 134 data points show the typical behaviour of Li versus temperature, with the Li dip at around 6400 K, the stars on the hot side with the highest Li values (likely not depleted), and members on the cool side of the dip already showing temperature-dependent depletion even for such a relatively young age. Second, whilst for the GES and AMBRE surveys neither Fu et al. nor Guiglion et al. provide an age distribution for the stars in their samples, we note that for GES
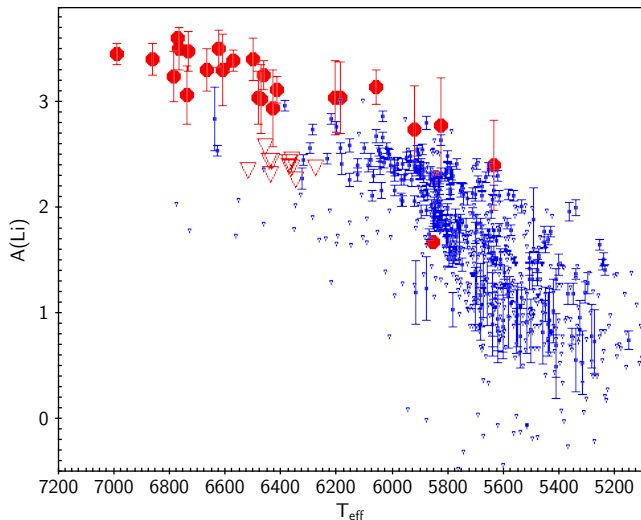
Fig. 3. Lithium abundance as a function of effective temperature for metal-rich ([Fe/H] > 0) GES MW field stars (blue points) and Ruprecht 134 (red points). Circles and triangles indicate Li detections and upper limits, respectively. We do not indicate T_{eff} errors in order to have a clean plot. For the MW and for Ruprecht 134 the errors are of the order of 50−100 K.

Thompson et al. (2018) demonstrated that the adopted selection criteria penalise stars younger than 2 Gyr, and that the sample is biased towards stars with ages between 2 and 5 Gyr. We therefore have evidence that these surveys observe metal-rich stars in the field that are cooler than the dip and older than 1 Gyr, and have hence undergone Li depletion. Our maximum Li value for the metal-rich stars is indeed substantially higher (a factor of two-three) than the values observed among field stars surveys. We therefore conclude that with OCs we sample a young hot population of metal-rich stars that is not sampled by present surveys of the MW field. This population does not show any decrease in Li with respect to solar-metallicity stars.

4. Conclusions

In this work we assume that the Li ISM at a given metallicity is well represented by the average Li abundance of OC members warmer than the Li dip, or PMS stars in very young clusters. Based on a sample of 18 OCs, we find that clusters with [Fe/H] < −0.1 show a maximum Li ∼ 3.1, while the solar- and supersolar-metallicity stars all have higher values, which peak at A(Li) ∼ 3.4 for the two most metal-rich objects. A shallow Li gradient may also be present. Therefore, our results do not support the claim that Li decreases in the ISM for high metallicity, at least up to [Fe/H] = 0.3. On the contrary, if anything a mild increase may be present.

We suggest that the discrepancy between our results and those of other studies can be fully explained because spectroscopic surveys observed old metal-rich MW field stars on the cool side of the Li dip that already suffer noticeable MS Li depletion when a few hundred million years old. Since the observed metal-rich stars tend to be relatively old, their highest Li abundance is 0.2−0.3 dex lower than the original value, and can be considered only as a loose lower limit to the ISM Li abundance. In other words, our results strongly indicate that the observed decrease in Li for metal-rich field stars is not "real"; rather, it is due to stellar evolution and lithium depletion mechanisms, and it is enhanced by sample selection effects.

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