

# Chemical evolution of the Galactic bulge as traced by microlensed dwarf and subgiant stars

## VII. Lithium<sup>★,★★</sup>

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### ABSTRACT

Lithium abundances are presented for 91 dwarf and subgiant stars in the Galactic bulge. The analysis is based on line synthesis of the <sup>7</sup>Li line at 6707 Å in high-resolution spectra obtained during gravitational microlensing events, when the brightnesses of the targets were highly magnified. Our main finding is that bulge stars at sub-solar metallicities that are older than about eight billion years do not show any sign of Li production; that is, the Li trend with metallicity is flat or even slightly declining. This indicates that no lithium was produced during the first few billion years in the history of the bulge. This finding is essentially identical to what is seen for the (old) thick disk stars in the solar neighbourhood, and adds another piece of evidence for a tight connection between the metal-poor bulge and the Galactic thick disk. For the bulge stars younger than about eight billion years, the sample contains a group of stars at very high metallicities at [Fe/H] ≈ +0.4 that have lithium abundances in the range  $A(\text{Li}) = 2.6\text{--}2.8$ . In the solar neighbourhood the lithium abundances have been found to peak at  $A(\text{Li}) \approx 3.3$  at [Fe/H] ≈ +0.1 and then decrease by 0.4–0.5 dex when reaching [Fe/H] ≈ +0.4. The few bulge stars that we have at these metallicities seem to support this declining  $A(\text{Li})$  trend. This could indeed support the recent claim that the low  $A(\text{Li})$  abundances at the highest metallicities seen in the solar neighbourhood could be due to stars from the inner disk, or the bulge region, that have migrated to the solar neighbourhood.

**Key words.** gravitational lensing: micro – Galaxy: bulge – Galaxy: formation – Galaxy: evolution – stars: abundances

## 1. Introduction

The Li abundance trends in the Milky Way disk and halo have been extensively mapped in the last two decades by high-resolution spectroscopic studies of nearby stars (e.g. [Chen et al. 2001](#); [Lambert & Reddy 2004](#); [Ghezzi et al. 2010](#); [Ramírez et al. 2012](#); [Delgado Mena et al. 2014](#); [Guiglion et al. 2016](#); [Pavlenko et al. 2018](#); [Bensby & Lind 2018](#)). The collective consensus is that the amount of Li observed in metal-poor halo stars lies at a level of about  $A(\text{Li}) \approx 2.2\text{--}2.3$  and that it remains essentially at this level over a wide range of metallicities up to at least [Fe/H] ≈ −1 ([Spite & Spite 1982](#)). At the very lowest metallicities below [Fe/H] ≲ −4, a decreasing trend is shown (e.g. [Sbordone et al. 2010](#); [Bonifacio et al. 2018](#)). At higher metallicities (greater than about [Fe/H] ≳ −1) where the Galactic

disk(s) dominate, the Spite plateau extends to about [Fe/H] ≈ −0.6, after which the Li trend shows a steep increase, peaking at  $A(\text{Li}) \approx 3.2$  around, or slightly above, solar metallicities. However, if only (thick) disk stars with ages greater than about eight billion years are considered the Li trend above [Fe/H] = −1 remains flat, or slightly declining, towards solar metallicities ([Bensby & Lind 2018](#)). On the other hand, if (thin) disk stars younger than about eight billion years are considered, the increasing Li trend towards and beyond solar metallicities emerges. At the very highest metallicities ([Fe/H] ≳ +0.2), the Li trend again shows a tendency of decreasing with [Fe/H] ([Delgado Mena et al. 2015](#); [Guiglion et al. 2016](#); [Fu et al. 2018](#); [Bensby & Lind 2018](#)).

This varying Li trend with metallicity in various stellar populations shows that Li is not only produced in stars but also depleted. While the depletion process is fairly well understood, the production sites are widely debated. Small amounts of Li were made in the Big Bang nucleosynthesis, theoretically putting it at a level of 2.6–2.7 (e.g. [Cyburt et al. 2016](#)). This is in contrast with the observations on the Spite plateau observed in metal-poor stars, which is about 0.4 dex lower and is often considered as the primordial value. This cosmological Li problem remains unsolved (e.g. [Meléndez et al. 2010](#); [Sbordone et al. 2010](#)).

\* Table 1 is only available at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](ftp://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/634/A130>

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The non-increasing Li trend in the local thick disk means that no Li was produced during the thick disk era that took place during the first few billion years of the Milky Way. Only later, in the thin disk, the Li trend increases strongly signalling the first production of Li since the Big Bang. Possible Li production sites include supernovae type II, cosmic rays, asymptotic giant branch (AGB) stars, red giant branch (RGB) stars, and novae (e.g. D'Antona & Matteucci 1991; Romano et al. 1999). Romano et al. (2001) explored the contribution of the different sources in their two-infall chemical evolution model of the Milky Way and found that the most important contributors were low-mass red giants and that novae were needed to reproduce the steep rise in the Li trend at higher metallicities. This has recently been further investigated by Cescutti & Molaro (2019), who indeed confirm that novae most likely are responsible for the production of the great majority of the Galactic Li (see also Matteucci 2010). At the same time Cescutti & Molaro (2019) show that core-collapse supernovae, RGB, and AGB stars are less significant Li production sites and can to a large degree be neglected compared to the amounts of Li being produced in novae and to some degree in cosmic ray spallation processes.

The recent discovery of a decreasing Li trend at the very highest metallicities is an unexpected result and several explanations have been proposed. First, it is possible that metal-rich stars are less efficient in producing Li. However, the current models of stellar evolution and nucleosynthesis do not support such a scenario, as it means that Li that is being produced in stars is starting to decline during the last few billion years and would be the first element showing this behaviour (Prantzos et al. 2017). Another possibility could be that the apparent decline in the Li trend in the solar neighbourhood is due to stars that have migrated here from the inner disk region, or even the bulge region, and that they show a lower Li abundance due to a faster star formation history in the inner disk (or bulge) regions (Guiglion et al. 2019). Grisoni et al. (2019) provide a new explanation, in which novae are the main Li producers and the decline at the highest metallicities could be due to a metallicity-dependent fraction of the binary systems that are novae precursors. No satisfactory explanation has so far been provided as to whether the migration scenario or the metallicity-dependent binary fraction scenario is preferred.

The observational data that has been considered so far are to a large degree confined to the solar neighbourhood (see references above). Even though large spectroscopic surveys, such as the *Gaia*-ESO survey (Gilmore et al. 2012) and GALAH (De Silva et al. 2015) reaching farther out in the disk, and recent results also include Li (Fu et al. 2018; Buder et al. 2018), they do however not reach into the very inner or outer disk regions. Li in the bulge is particularly poorly constrained, and as the bulge is a major structural component of the Milky Way, this hampers our ability to get a complete view of the production and depletion of Li in the Milky Way. Also, an interesting aspect of the bulge is that it contains some of the most metal-rich stars ever observed, reaching  $[\text{Fe}/\text{H}] \gtrsim +0.5$ . It could therefore provide hints about the Li decline seen in local dwarf samples, if this decline is also present in the bulge stars, and whether it continues at the even higher metallicities seen in the bulge. The few studies that have measured Li abundances in bulge stars have mainly done so using RGB stars (Gonzalez et al. (2009), Lebzelter et al. (2012) or AGB stars (Uttenhaler et al. 2007). These stars do however not reflect the native Li abundance that they were born with owing to the deep convection zones in the outer regions of their atmospheres that bring down Li to warmer regions where it is destroyed. Li in dwarf stars warmer than about 5800 K are not

affected by this. Dwarf stars in the bulge are however very faint and are very difficult to observe under normal circumstances.

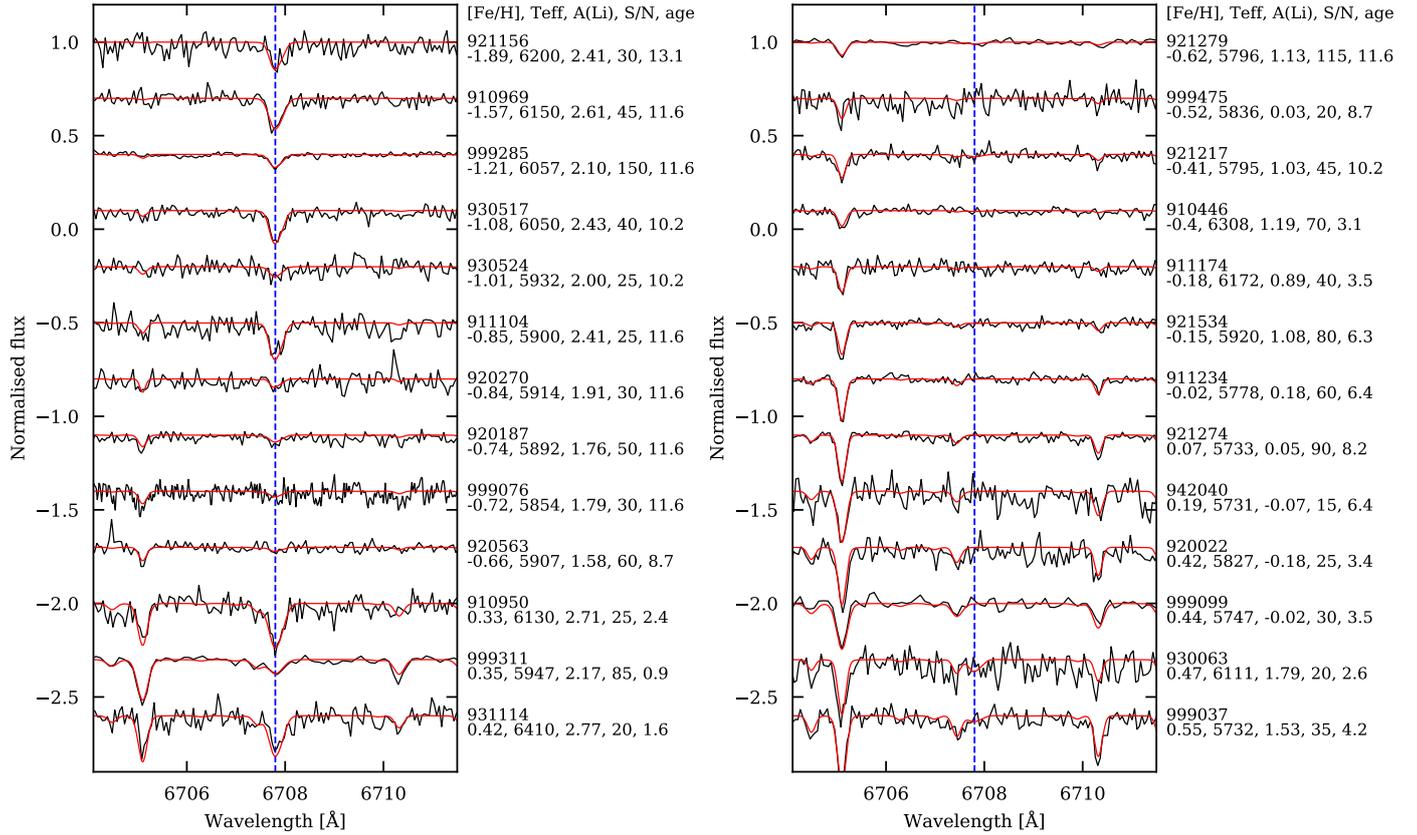
In Bensby et al. (2017) we present detailed elemental abundances and stellar ages for 91 microlensed dwarf and subgiant stars in the Galactic bulge. This work shows that the bulge has very complex age and abundance distributions, and that it most likely consists of stars from the other Galactic stellar populations. In particular, we find the metal-poor bulge and thick disk have very similar abundance trends (see also Meléndez et al. 2008; Alves-Brito et al. 2010; Bensby et al. 2011, 2013; Gonzalez et al. 2011; Jönsson et al. 2017), that they have similar ages that in general are greater than about 8 Gyr, and that the metal-rich bulge in some ways resemble what is observed in the local thin disk.

Regarding Li in the bulge, Minniti et al. (1998) used microlensing events to study bulge dwarf stars and claimed a detection of Li in MACHO-1997-BLG-45/47. Later, Cavallo et al. (2003) re-analysed the spectrum obtained by Minniti et al. (1998) and could not confirm the Li detection owing to the limited signal-to-noise ratio (S/N). The first clear detection of Li in an un-evolved dwarf star was presented in Bensby et al. (2010) for the metal-poor bulge dwarf MOA-2010-BLG-285S, and for another five microlensed bulge dwarf stars in Bensby et al. (2011), for which the Li line could be detected. These studies showed that the metal-poor bulge dwarf stars have Li abundances consistent with the Spite plateau, and that the more metal-rich dwarf stars a large spread in Li. In this study we use the now larger sample of microlensed bulge dwarf stars to investigate whether the distinct Li trends seen in the solar neighbourhood also persist in the bulge. If so, this would be another clear indication of the connection between the bulge and the disk(s). If possible we also aim to explore Li abundances at the very highest metallicities. The bulge contains the most metal-rich stars ever observed and should be the optimal place to explore whether the declining Li trend with metallicity is also present there.

## 2. Abundance analysis

We analyse Li for the full sample of 91 microlensed dwarf stars using the same methodology as in Bensby & Lind (2018) where Li was investigated for the 714 nearby thin and thick disk stars from Bensby et al. (2014). In summary, Li abundances are determined through spectral line synthesis of the  ${}^7\text{Li}$  line at 670.7 nm. For the line synthesis we used the Uppsala MARCS model atmospheres (Gustafsson et al. 2008) together with SME (Valenti & Piskunov 1996) as a spectral synthesiser. The linelist and atomic data are the same as in Bensby & Lind (2018). Input stellar parameters and their uncertainties were adopted from Bensby et al. (2017) in which the sample is described in detail. Out of the 91 microlensed bulge dwarfs, the Li line was detected and Li abundances determined for 22 stars. For the remaining 69 stars only upper limits on the Li abundance could be estimated. These non-detections are most likely due to the wide variation in the S/N of the obtained microlensed dwarf star spectra, meaning that the Li line could not be resolved from the continuum noise in many cases.

We show in Fig. 1, on the left-hand side, the observed and the best-fitting synthetic spectra for 13 stars that have  $T_{\text{eff}} > 5800$  K and have estimated Li abundances. In most stars the Li line is clearly visible, even in those stars in which the S/N is getting low around  $S/N = 25\text{--}30$ . Figure 1, right-hand side, shows the observed spectra for the 13 stars that have  $T_{\text{eff}} > 5700$  K, and for which we could only determine upper limits on the Li abundances.



**Fig. 1.** *Left-hand side:* normalised spectra for 13 stars that have  $T_{\text{eff}} > 5800$  K and where the Li line at 6707.8 Å could be detected and the Li abundance measured. The vertical dotted line shows the wavelength where the Li line is located and the red solid lines show the best-fitting synthetic spectra. *Right-hand side:* normalised spectra for 13 stars that have  $T_{\text{eff}} > 5700$  K and where the Li line at 6707.8 Å could not be detected, and only  $A(\text{Li})$  upper limits could be determined. The vertical dotted line shows the location where the Li line should be. For each spectrum we give  $[\text{Fe}/\text{H}]$ ,  $T_{\text{eff}}$ ,  $A(\text{Li})$ , the measured S/N per pixel, and the age of the star.

Li abundances are sensitive to changes in  $T_{\text{eff}}$ , while hardly at all to changes in  $\log g$  and  $[\text{Fe}/\text{H}]$ . Random uncertainties were estimated by varying the effective temperatures according to their uncertainties given in Bensby et al. (2017). This gives upper and lower limits to the Li abundances. Non-local thermodynamical equilibrium (NLTE) corrections from Lind et al. (2009) were added to the Li abundances. The Li abundances, Li uncertainties, and applied NLTE corrections are given in Table 1.

Systematic uncertainties are difficult to estimate, but as we compare our derived Li abundances to the Li abundances for the sample of 714 nearby F and G dwarf stars, for which the exact same methods have been applied, the relative uncertainties should be at a minimum between these studies. Bensby et al. (2017) also compare the Li abundances for stars in common with Ramírez et al. (2012) and Delgado Mena et al. (2015) and find good agreement.

### 3. Results

#### 3.1. Li and effective temperature

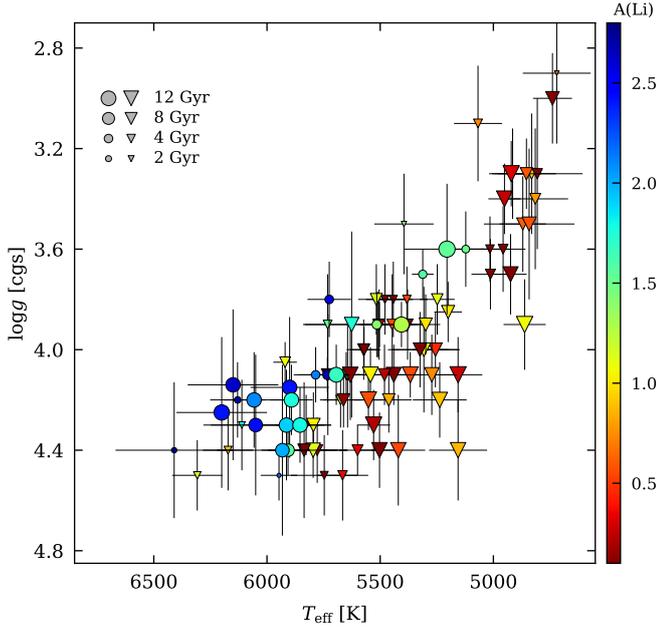
Figure 2 shows an Hertzsprung Russell diagram for the microlensed bulge stars. The highest Li abundances are, as expected, seen for the stars with the highest temperatures in the turn-off region. This agrees with the findings in Bensby & Lind (2018), which use the exact same methods as this study and other studies (see references in Sect. 1). The microlensed bulge stars also show the general increase in Li abundance with effective

**Table 1.** Li abundances for the microlensed bulge dwarfs.

Name	Nr	$A(\text{Li})$	$A(\text{Li})_l$	$A(\text{Li})_h$	$\Delta_{\text{NLTE}}$	Flag
⋮	⋮	⋮	⋮	⋮	⋮	⋮
MOA-2010-BLG-167S	910167	1.27	1.22	1.31	0.08	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮

**Notes.** For each star we give the NLTE corrected  $A(\text{Li})$  abundance and the low and high values determined by changing the effective temperatures by their uncertainties. The Li NLTE corrections that were added are also given. The last column is a flag where the value “0” means that it is a value from a well-fitted line. A value of “1” means that the Li abundance is an upper limit. All other parameters are given in Bensby et al. (2017) in which the two identifiers (Name and Nr) are given in the same way for easy cross-matching. This table is only available in electronic form at the CDS.

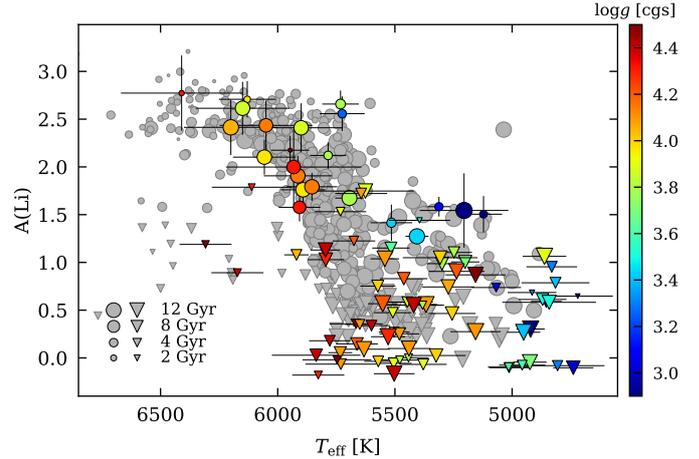
temperature, which has been seen in most studies of Li. This is shown in Fig. 3, and it is evident that the bulge dwarfs follow the same pattern as outlined by the sample of 714 nearby disk stars from Bensby & Lind (2018). The decline with decreasing temperature is a result of Li being destroyed in stars cooler than about 5800 K. To trace the Galactic chemical evolution of Li, we therefore need to consider stars with sufficiently high temperature so that the observed surface abundance of Li has not been affected by processes internal to the star. The sample contains



**Fig. 2.** Hertzsprung Russell diagram for microlensed dwarf sample. The stars are colour coded based on the measured Li abundances (according to the colour bar on the right-hand side). Triangles represent those stars for which only upper abundance limits could be determined. The sizes of the markers are scaled with the estimated ages of the stars.

19 stars with effective temperatures higher than 5800 K, and six of those only have upper limit estimates of the Li abundances.

There are three bulge stars with  $6100 \leq T_{\text{eff}} \leq 6300$  K, which have Li upper limits significantly below  $A(\text{Li}) < 2.0$  (star no. 910446, where  $T_{\text{eff}} = 6308$  K and  $A(\text{Li}) = 1.19$ ; star no. 911174, where  $T_{\text{eff}} = 6172$  K and  $A(\text{Li}) = 0.89$ ; and star no. 930063, where  $T_{\text{eff}} = 6111$  K and  $A(\text{Li}) = 1.79$ ; see Fig. 1). Similar stars can also be seen in the Bensby & Lind (2018) sample (see Fig. 3). The explanation for the low Li abundances in these stars is uncertain. They are not hot enough to be part of the dip-like feature that appears in  $A(\text{Li})$  versus  $T_{\text{eff}}$ , centred around 6700 K (Boesgaard et al. 2016), and that was first seen in open clusters (Boesgaard & Tripicco 1986). On the other hand there is a possibility that they could be blue straggler stars, which observationally are well established to show essentially no measurable Li (e.g. Glaspey et al. 1994; Carney et al. 2005). For instance, a few hot halo dwarf stars that are ultra-Li-depleted have been suggested to be blue stragglers (Ryan et al. 2001) have been recently confirmed by Bonifacio et al. (2019). While the exact formation scenario of blue stragglers is not settled, blue stragglers formed by binary star coalescence show a very strong Li depletion (more than 5 dex); collisional blue stragglers show some remaining Li at the level  $A(\text{Li}) \approx 1.1$  (Glebbeek et al. 2010), which agrees reasonably with the upper limit Li abundances for two of the three bulge stars (bulge star no. 910446 and 911174). The metallicities of these two stars are  $[\text{Fe}/\text{H}] = -0.41$ , and  $-0.18$ , respectively. If these two stars indeed were to be considered as blue straggler stars, their stellar age estimates could be too young. However, in the case of the solar analogue HIP 10725, which has several signatures of blue stragglers, such as non-detectable lithium, non-detectable beryllium, and large excess of neutron capture elements, just a small amount of mass transferred (less than  $0.01 M_{\odot}$ ) was enough to introduce the observed excess of n-capture elements; as a consequence of the extra-mixing because of the transfer of angular momentum, lithium and beryllium were depleted (Schirbel et al. 2015). So, even if there are



**Fig. 3.** Li abundances vs.  $T_{\text{eff}}$  for the microlensed dwarf sample. Triangles represent those stars for which we could only determine upper limits on the abundances. The grey circles and triangles in the background represent the 714 stars from Bensby et al. (2014) for which Li abundances are determined in Bensby & Lind (2018) in the exact same way as for the microlensed bulge dwarfs. The sizes of the markers are scaled with the estimated ages, and the bulge stars are also colour coded based on their surface gravities according to the colour bar on the right-hand side.

signatures of a blue straggler phenomenon, the age may not change much, except of course in more dramatic cases such as a star merger or significant mass transfer. In any case, the presence or lack of presence of blue stragglers in our sample does not affect our conclusions regarding the Galactic evolution of Li as it is based on stars in which Li is readily detected and measured.

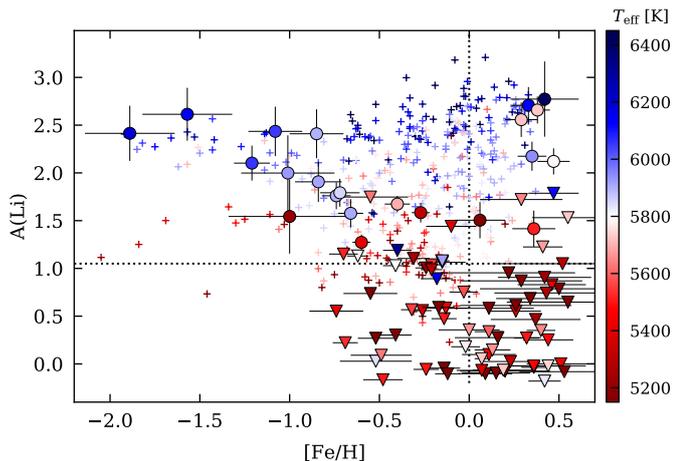
### 3.2. Li and metallicity

Figure 4 shows the results in the  $A(\text{Li})$ – $[\text{Fe}/\text{H}]$  plane with the nearby disk stars from Bensby & Lind (2018), following the same colour coding, in the background. There are ten bulge stars at  $[\text{Fe}/\text{H}] \lesssim -0.6$  that have  $T_{\text{eff}} > 5800$  K; at the metal-poor end, within the uncertainties, these follow the Spite plateau as also outlined in this work by the disk stars in the background. The  $A(\text{Li})$  trend appears to decrease to lower  $A(\text{Li})$  values with  $[\text{Fe}/\text{H}]$  as one approaches  $[\text{Fe}/\text{H}] \approx -0.6$ . Considering the six stars that have  $T_{\text{eff}} > 5800$  K and upper limit  $A(\text{Li})$  in the metallicity range  $-0.4 \lesssim [\text{Fe}/\text{H}] \lesssim -0.2$  the declining  $A(\text{Li})$  trend might continue to even higher metallicities.

At super-solar metallicities the sample only contains three stars with  $T_{\text{eff}} > 5800$  K, which at the same time have well-determined Li abundances. These stars are grouped at the very highest metallicities around  $[\text{Fe}/\text{H}] \approx 0.3$ – $0.4$  and they follow the general  $A(\text{Li})$  trend as outlined by the nearby disk stars. There are also two stars with  $T_{\text{eff}} > 5800$  K at these high metallicities that have upper limit measurements at even lower  $A(\text{Li})$  values: one at  $A(\text{Li}) \approx 1.6$  and one at  $A(\text{Li}) \approx -0.2$ . In the metallicity range  $-0.6 \lesssim [\text{Fe}/\text{H}] \lesssim +0.3$  the sample only contains a few stars with well-determined Li abundances, all of which have temperatures below 5800 K. The stars with  $T_{\text{eff}} > 5800$  K in this metallicity range have upper limits on the Li abundances, meaning that it is difficult to reliably trace how Li has evolved at higher metallicities.

### 3.3. Li, metallicity, and age

Figure 5 again shows the Li abundances versus  $[\text{Fe}/\text{H}]$  plane for the microlensed bulge dwarfs, but this time the sample is



**Fig. 4.** Li abundances vs.  $T_{\text{eff}}$  for the microlensed dwarf sample. The stars are colour coded based on the effective temperatures of the stars. Triangles represent those stars for which we can only determine upper limits on the abundances. The grey plus signs in the background represent the 714 stars from [Bensby et al. \(2014\)](#) for which Li abundances were determined in [Bensby & Lind \(2018\)](#) in the exact same way as for the microlensed bulge dwarfs. The dotted lines show the solar values with the solar photospheric Li abundance taken from [Asplund et al. \(2009\)](#).

divided into a young sub-sample with stars younger than 8 Gyr and an old sub-sample with stars older than 8 Gyr. This division is inspired by the recent study of Li in the local disk by [Bensby & Lind \(2018\)](#), which shows two distinctly different Li trends by dividing the sample at 8 Gyr. The old disk sample is representative of the thick disk and the young disk sample of the thin disk (see also [Bensby et al. 2014](#)). A separation between the thin and thick disks at about 8 Gyr has been seen in other studies as well (e.g. [Haywood et al. 2013](#); [Bensby et al. 2014](#); [Kilic et al. 2017](#); [Silva Aguirre et al. 2018](#)).

Figure 5 shows the running mean of the Li abundances for the disk stars, and the dispersion around the running mean based on the (up to) six stars with the highest Li abundances that have  $T_{\text{eff}} > 5800$  K. For the old disk sample the  $A(\text{Li})$  trend is slightly decreasing with  $[\text{Fe}/\text{H}]$  (red line in Fig. 5a), and for the young disk sample it is increasing with  $[\text{Fe}/\text{H}]$  until solar metallicities, after which it declines towards the highest metallicities (blue line in Fig. 5b).

Within the uncertainties, the old bulge sub-sample with  $T_{\text{eff}} > 5800$  K follows the Li abundance pattern outlined by the old disk dwarfs in the solar neighbourhood. The metal-poor stars tend to align with the Spite plateau ([Spite & Spite 1982](#)); for the metal-rich part of the sample we see a declining trend as seen in the solar neighbourhood, meaning that no Li production took place during the first few billion years, coinciding with the era of the thick disk. It could be argued that this declining  $A(\text{Li})$  trend with  $[\text{Fe}/\text{H}]$  is an effect due to destruction of Li within the stars, as the stars at higher metallicities generally appear to have lower temperatures. However, within the small groups of stars hotter than 6000 K, which should have not had any internal depletion, and between 5800–6000 where Li might start to show some depletion, it is evident that the  $A(\text{Li})$  trend is not increasing with metallicity.

For the bulge stars that are younger than 8 Gyr and that have  $T_{\text{eff}} > 5800$  K, we have three stars with well-determined Li abundances and five stars with upper limits. The two bulge stars with the highest Li abundances at  $[\text{Fe}/\text{H}] \approx +0.4$  have  $A(\text{Li}) \approx 2.8$ ,

and seem to continue on the declining  $A(\text{Li})$  trend with  $[\text{Fe}/\text{H}]$  as outlined by the disk stars.

## 4. Discussion

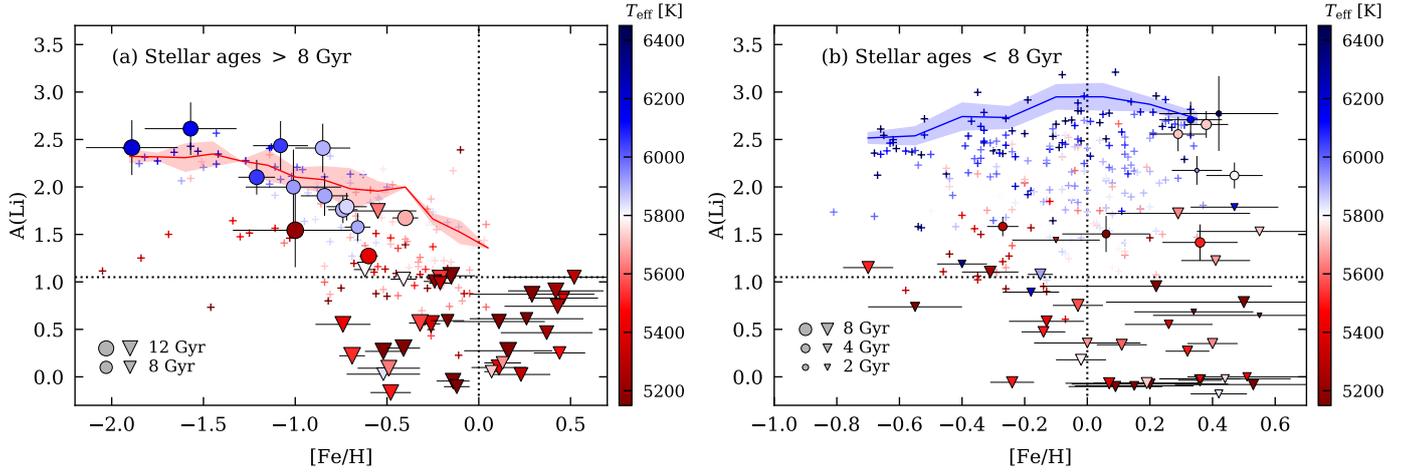
### 4.1. Evolution of Li in the bulge

[Grisoni et al. \(2019\)](#) modelled the evolution of Li in the Milky Way and concluded that the main producer of Galactic Li is novae. By assuming that the fraction of binaries, which are supposed to be the novae progenitors, decrease with increasing metallicity, they also could provide an explanation for the decrease in  $A(\text{Li})$  seen at the very highest metallicities. The thin dash-dotted lines in Fig. 6 shows the models from [Grisoni et al. \(2019\)](#) in which Li is produced by novae. There are several novae models shown, representing different laws for the fraction of binary systems that give rise to novae (see [Grisoni et al. 2019](#) for more details). The solid thick line shows the total production of Li in the disk and includes other sources that are less significant, such as AGB stars, cosmic rays, and massive stars. The evolution of Li in the thick disk is shown by the thick dashed line, and the rise at solar metallicities is caused by Li production in novae that starts to contribute to the Galactic Li enrichment about one billion years after the beginning of Galaxy formation ([Grisoni et al. 2019](#)). The thin dashed line shows the model for the Galactic bulge, which [Grisoni et al. \(2019\)](#) assumes to be a classical bulge population, meaning no young stars, only an old classical spheroid. In that case the bulge evolved much faster than any of the disks, and long-lived stars did not have time to enrich the interstellar medium. For comparison purposes the thick dash-dotted line shows the Li evolution under pure astration, that is, no Li is produced at all.

In Fig. 6 we compare the Li abundances for the microlensed bulge dwarfs to the models from [Grisoni et al. \(2019\)](#). To enhance the comparison, we excluded stars with  $T_{\text{eff}} < 5700$  K and as the colour coding with temperature is the same as in the other figures, stars that have  $T_{\text{eff}} < 5800$  K are indicated in red. The figure also includes the running median Li abundances for the nearby thick disk stars and the nearby thin disk stars from [Bensby & Lind \(2018\)](#).

The  $A(\text{Li})$ – $[\text{Fe}/\text{H}]$  trend for the bulge stars older than about 8 Gyr compares well with the trend for the local thick disk stars, and there is no indication of an increase in Li for the old bulge stars or for the nearby thick disk at higher metallicities. The lack of bulge stars with well-determined Li abundances around solar metallicities makes it impossible to say if this truly is the case, or whether the thick disk model from [Grisoni et al. \(2019\)](#) that shows the Li increase at  $[\text{Fe}/\text{H}] \approx -0.2$  (thick dashed line) is a proper representation. At the same time we see that there are a few stars at these metallicities that have  $T_{\text{eff}} > 5800$  K and for which only upper Li estimates could be given. Whether these stars were born with lower Li abundances or not remains unclear, but it is unlikely that they should have the high Li abundances corresponding to the thin disk or thick disk models by [Grisoni et al. \(2019\)](#).

The few young (age less than about 8 Gyr) bulge stars with  $T_{\text{eff}} > 5700$  K, which have Li abundance estimates, are all located at very high metallicities, most of which in such a way as they appear to extend on the local thin thick disk Li trend. Interestingly, the same region is also the crossing area for the [Grisoni et al. \(2019\)](#) models of Li enrichment from massive stars and cosmic rays. If we were to assume that the bulge is single classical bulge and the microlensed dwarf stars then all belonged to this population, the match with the model showing the Li



**Fig. 5.** Li abundances vs.  $[\text{Fe}/\text{H}]$  for the microlensed dwarf sample for stars older than 8 Gyr (*upper plot*) and for stars younger than 8 Gyr (*lower plot*). The stars are colour coded based on their effective temperatures (according to the colour bar on the right-hand side). Triangles represent those stars for which we could only determine upper limits on the abundances. The sizes of the circles and triangles are scaled by the ages of the stars, as shown in the lower left corners of the plots. The coloured plus signs in the background of each plot represent the stars from the sample of 714 stars from [Bensby et al. \(2014\)](#) that are older and younger than 8 Gyr, respectively. The red and blue solid lines and the red and blue shaded regions show the running mean Li abundance and the dispersion around the mean, calculated from the (up to) six stars with the highest Li abundances that have  $T_{\text{eff}} > 5800$  K, in steps of 0.15 dex and with a bin size of 0.2 dex for the nearby disk stars. The dotted lines show the solar values with the solar photospheric Li abundance taken from [Asplund et al. \(2009\)](#).

production by massive stars would be striking. However, if this were the case, as the massive stars in the model contribute on a very short timescale, the metal-rich stars would have to be old, i.e. older than about eight to ten billion years, as all the metal-poor bulge stars appear to be. This is clearly not the case; the metal-rich stars in Fig. 6 are below four billion years in age. So, we cannot make that connection or conclusion. Instead, if the bulge is a mixture of the other major stellar populations in the Milky Way, in particular the thin and thick disks, the age and location of these few stars at the metal-rich end of the  $A(\text{Li})$  trend connects them nicely to the thin disk. Also, their Li abundances seem to add further pieces of evidence of a declining  $A(\text{Li})$  trend at super-solar metallicities. We should, however, caution that as we are lacking (young) stars with effective temperatures higher than 5800 K around solar metallicities, this statement is not conclusive. Maybe it could also be that the Li abundances in the metal-rich bulge dwarfs hint at a different evolutionary path in the inner parts of the Milky Way, where novae have not played a major role, but instead cosmic rays have provided the necessary Li enrichment. More observations of relatively hot dwarf stars in the bulge are clearly needed to put this on firm ground.

#### 4.2. Radial migration of inner disk/bulge stars

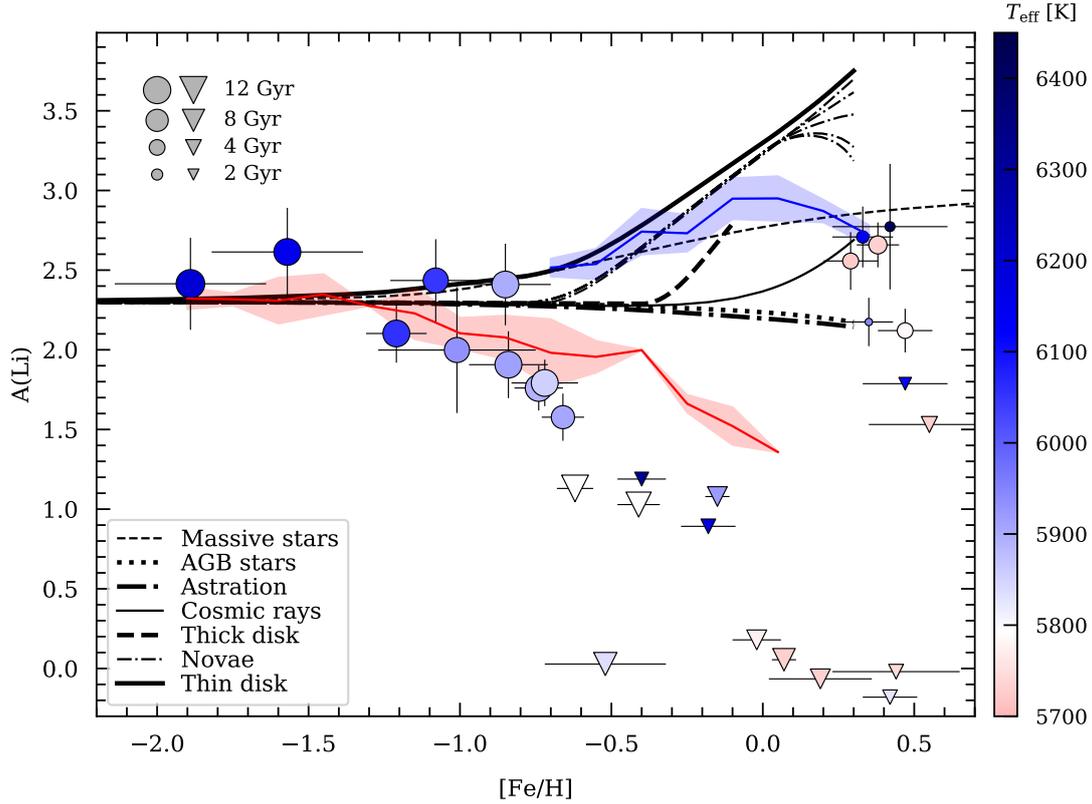
Recent developments in modelling of radial migration has indicated that the most metal-rich and kinematically cold stars migrate the most. For instance, [Minchev et al. \(2018\)](#) show that the stars in the metal-rich tail of the local metallicity distribution most likely were born at galactocentric radii smaller than about 4 kpc. If the Li enrichment of the inner bulge region, or inner disk, has had a different Li enrichment than the rest of the Milky Way disk, and if some of those stars migrated to the solar neighbourhood, could they be the answer to the decreasing Li trend at super-solar metallicities? This is the proposed solution by [Guiglion et al. \(2019\)](#), who claim that the inner disk stars have experienced a faster enrichment and therefore a delayed Li production, meaning that the Li increase occurs at higher  $[\text{Fe}/\text{H}]$  than in the local disk. In fact, the metal-rich bulge stars in our

sample do not reach as high Li abundances as seen in the local dwarf sample around  $[\text{Fe}/\text{H}] \approx 0$ , instead they cluster around  $A(\text{Li}) \approx 2.5\text{--}2.8$ , appearing to extend on the declining  $A(\text{Li})$  trend seen in the local disk stars (see Fig. 6). Again, our sample does not contain any warm stars  $T_{\text{eff}} > 5800$  K with well-determined Li abundances around  $[\text{Fe}/\text{H}] \approx 0$ . This would have allowed us to distinguish between a continuously increasing Li trend in the bulge and a Li trend in the bulge that would have been similar to the local thin disk, that is, increasing towards solar metallicities and then declining. Currently we cannot rule out either of the two. We also note that [Pompéia et al. \(2002\)](#) analysed Li in a sample of bulge-like dwarf stars, which have eccentric orbits with pericentric distances as small as 2–3 kpc, and found a large scatter in  $A(\text{Li})$  and no apparent trend with  $[\text{Fe}/\text{H}]$ .

#### 4.3. Similarities between the bulge and local disk

Several studies have claimed that the bulge, rather than being a single unique stellar population, contains contributions from the other main Galactic stellar populations (in particular the thin and thick disks) and that they happen to overlap in the bulge region (e.g. [Ness et al. 2013](#); [Bensby et al. 2017](#)). Apart from a multimodal metallicity distribution, the observed abundance trends in the bulge agree very well with the abundance trends in the local thin and thick disks (see references in Sect. 1), which could point to possible connections between the populations and their evolutionary histories.

These similarities between the bulge and local disks continue with Li. The observed  $A(\text{Li})$  versus  $[\text{Fe}/\text{H}]$  trend in the (old) metal-poor bulge remains flat (or could even be slightly declining) and almost perfectly follows the observed trend in the local (old) thick disk. This indicates that no Li was produced during the first few billion years of the bulge or in the first few billion years of the thick disk era (as shown by [Bensby & Lind 2018](#)). The Li detections in microlensed dwarf sample at super-solar metallicities have poor statistics, but the few most metal-rich bulge stars Li abundances that extend on the decreasing Li trend



**Fig. 6.** Comparison between the microlensed bulge dwarfs, the running mean  $A(\text{Li})$  trends for the thin disk (younger than 8 Gyr, blue line), and thick disk stars (older than 8 Gyr, red line) from [Bensby & Lind \(2018\)](#), and the different  $A(\text{Li})$  evolution models from [Grisoni et al. \(2019\)](#). The microlensed dwarf stars are colour coded with their effective temperatures (same scale as in previous figures) and their sizes are scaled based on the estimated ages. The figure only includes bulge stars with effective temperatures greater than 5700 K. The different chemical evolution models of Li are indicated in the legend.

are seen in the local disk. We cannot, however, claim that this is truly the case, or whether the bulge has experienced a delayed Li enrichment due to faster chemical enrichment in the inner regions of the galaxy. It is clear, however, that the few metal-rich stars are young and cannot be part of any classical bulge component.

## 5. Summary

We have determined Li abundances in 91 dwarf and subgiant stars in the Galactic bulge. For 22 of the stars the Li line at  $6707.8 \text{ \AA}$  could be detected and Li abundances could be well determined. For the remaining 69 stars upper limits for the Li abundance were estimated. The analysis was done by line synthesis of the  ${}^7\text{Li}$  line at  $6707.8 \text{ \AA}$  in spectra that were obtained when the targets were microlensed and their brightnesses highly magnified. The methodology of determining stellar parameters and Li abundances is identical to those in [Bensby et al. \(2014\)](#) and [Bensby & Lind \(2018\)](#), in which 714 local disk dwarf stars were analysed. This has enabled a truly differential comparison of the evolution of Li in the bulge and the local thin and thick disks. Our main findings are as follows:

- The  $A(\text{Li})$ – $[\text{Fe}/\text{H}]$  trend for the bulge stars older than 8 Gyr remains flat or might even slightly decline with increasing metallicity. This agrees very well with the Li trend that is observed in the local thick disk (stars older than 8 Gyr). This indicates that no Li was produced during the first few billion years of the bulge era, which happens to coincide with the

first few billion years of the thick disk era (where no indications of Li production can be seen either).

- The most metal-rich stars are young and have lithium abundances lower than the peak of the upper envelope of the Li distribution, which happens around  $[\text{Fe}/\text{H}] \approx 0$ . They appear to extend on the decline in  $A(\text{Li})$  at super-solar  $[\text{Fe}/\text{H}]$ , which has been seen in recent studies of local (thin) disk stars.

Whether the cause for the lower Li abundance in the most metal-rich bulge stars is because they are the products of a similar enrichment history, as seen in the local thin disk (with a maximum around solar metallicities and then a decline), or if they have followed another enrichment history, needs to be further investigated. There are no indications that the lower Li abundances in the most metal-rich bulge stars is due to delayed Li production as a consequence of faster chemical enrichment in the bulge. Then these stars would have been much older than their current age estimates of around three to four billion years. As the current sample is lacking stars around solar metallicities that have well-determined Li abundances, further observations are required to settle the question of the exact evolutionary path of Li in the metal-rich bulge.

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