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LETTER TO THE EDITOR

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

III. Detection of lithium in the metal-poor bulge dwarf MOA-2010-BLG-285S

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ABSTRACT

Context. In order to study the evolution of Li in the Galaxy it is necessary to observe dwarf or subgiant stars. These are the only long-lived stars whose present-day atmospheric chemical composition reflect their natal Li abundances according to standard models of stellar evolution. Although Li has been extensively studied in the Galactic disk and halo, to date there is only one uncertain detection of Li in an unevolved bulge star.
Aims. Our aim with this study is to provide the first clear detection of Li in the Galactic bulge, based on an analysis of a dwarf star that has largely retained its initial Li abundance.
Methods. We have performed a detailed elemental abundance analysis of the bulge dwarf star MOA-2010-BLG-285S using a high-resolution, and high signal-to-noise spectrum obtained with the UVES spectrograph at the VLT when the object was optically magnified during a gravitational microlensing event (visual magnification $A \sim 550$ during observation). The lithium abundance was determined through synthetic line profile fitting of the ^{7}Li resonance doublet line at 670.8 nm. The results have been corrected for departures from LTE.
Results. MOA-2010-BLG-285S is, at [Fe/H] = −1.23, the most metal-poor dwarf star detected so far in the Galactic bulge. Its old age (12.5 Gyr) and enhanced [α/Fe] ratios agree well with stars in the thick disk at similar metallicity. This star represents the first unambiguous detection of Li in a metal-poor dwarf star in the Galactic bulge. We find an NLTE corrected Li abundance of $\log\epsilon(\mathrm{Li}) = 2.16$, which is consistent with values derived for Galactic disk and halo dwarf stars at similar metallicities and temperatures.
Conclusions. Our results show that there are no signs of Li enrichment or production in the Galactic bulge during its earliest phases. Observations of Li in other galaxies (ω Cen) and other components of the Galaxy suggest further that the Spite plateau is universal.

Key words. Gravitational lensing: micro — Galaxy: bulge — Galaxy: formation — Galaxy: evolution — Stars: abundances

1. Introduction

Recent studies have shown agreement between the chemical evolution of the Galactic bulge and the thick disk (Meléndez et al. 2008; Alves-Brito et al. 2010; Bensby et al. 2010a,b). While many observations of Li in the Galactic halo and the disk(s) have been carried out, no measurement of the Li abundance in unevolved bulge stars have been secured. It is therefore unknown if the bulge Li abundance agrees with the Li plateau of the Galactic halo (Spite & Spite 1982), or if it shows the same types of depletion or enrichment that many of the disk stars do.

Li is the only element besides H and He that is produced in measurable amounts in the Big Bang with a predicted primordial ^{7}Li abundance of $\log\epsilon(\mathrm{Li}) \approx 2.72 \pm 0.05$ (e.g., Cyburt et al. 2008). At later stages, possible production sites for Li include cosmic rays (e.g., Reeves 1970), and AGB stars in certain mass ranges (e.g., Sackmann & Boothroyd 1999). However, Li is a fragile element which is destroyed in the interior of stars when the temperature exceeds about $2.5 \cdot 10^6$ K (e.g., Weymann & Sears 1965). The only stars that retain their initial Li surface abundances are dwarf and subgiant stars with effective temperatures in the range 6000 to 6500 K. Cooler dwarf stars have convective zones that mix the surface Li down to hotter regions where it is destroyed, while for hotter dwarf stars, at solar metallicities, Li is again destroyed (the so-called Li-dip, see, e.g., Boesgaard & Tripicco 1986). The solar Li abundance

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is a factor of 160 lower than measured in the most pristine meteorites (Asplund et al. 2009), which reflects a secular Li depletion over the past 4.5 Gyr (Baumann et al. 2010). As stars evolve to become red giant branch (RGB) stars, the Li abundance decreases due to the first dredge-up and later through extra mixing at the RGB bump (e.g., Iben 1965; Charbonnel & Zahn 2007; Lind et al. 2009b, and Pinsonneault 1997 for a general review on mixing in stars). This is also the reason why RGB stars cannot be used for Galactic chemical evolution studies of Li (although they can be safely used for many other elements).

Being confined to dwarf stars has given an incomplete and poorly understood picture on the Galactic evolution of Li. It is only for Galactic halo and disk stars in the solar neighbourhood for which Li has been unambiguously observed in dwarf stars. For instance, studies of metal-poor dwarf stars in the Galactic halo have revealed a cosmological Li problem: the measured Li abundance is a factor of 2 – 5 lower than predicted from standard Big Bang nucleosynthesis (BBNS) (e.g., Spite & Spite 1982; Asplund et al. 2006; Bonifacio et al. 2007; Aoki et al. 2009; Sbordone et al. 2010; Meléndez et al. 2010). The reasons for this are still unknown but both non-standard stellar Li depletion (e.g., Korn et al. 2006) and non-standard BBNS (e.g., Jedamzik & Pospelov 2009) have been invoked. Studies of the Galactic disk show a wide scatter of Li abundances, with many stars indicating that Li increases to very high levels as well as decreasing to very low levels (e.g., Lambert & Reddy 2004).

Dwarf stars in the bulge are usually too faint in order to get the high-resolution spectra needed to analyse Li. However, in a pioneering study on using microlensing events to study bulge dwarf stars, Minniti et al. (1998) 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 due to the limited S/N. Furthermore, in Bensby et al. (2010b) who analysed 15 microlensed bulge dwarfs, attempts were made to include MACHO-1997-BLG-45/47 as well, but it had to be excluded as the spectrum obtained by Minniti et al. (1998) was deemed of insufficient quality for a trustworthy abundance analysis. Hence, the Li detection in the bulge by Minniti et al. (1998) is uncertain. A few Li-rich RGB stars in the bulge have been discovered (Gonzalez et al. 2009). However, as explained above, such stars have not retained their original Li abundances but have experienced internal Li destruction as well as production.

In this Letter we present the result from a microlensing event toward the Galactic bulge for which we have obtained a high-resolution spectrum of high quality of the source star. The star is a dwarf star in the bulge that is sufficiently hot to not have developed a deep convective zone in its atmosphere, meaning that the initial Li abundance of the star is intact.

2. Observations and lens effects

MOA-2010-BLG-285S was identified as a possible high-magnification microlensing event toward the bulge at $(l, b) = (0.3, -2.6)$ deg in early June 2010 with the MOA alert system[1] (e.g., Bond et al. 2001). The intrinsic source flux (inferred from the microlensing model) indicated that the source star was a dwarf star and we triggered our ToO observations with the ESO Very Large Telescope (VLT) on Paranal on June 6. Using the UVES spectrograph (Dekker et al. 2000), configured with dichroic number 2, the target was observed for a total of two hours, split into three 40 minute exposures. The resulting spectrum was recorded on three CCDs with wavelength coverages between 376-498 nm (blue CCD), 568-750 nm (lower red CCD), and 766-946 nm (upper red CCD). A slitwidth of 1″ yielded a spectral resolution of $R \approx 45\,000$. The data were reduced with the UVES pipeline (version 4.4.5). The signal-to-noise (S/N) ratio per pixel at 670 nm is ~ 170. Before the observation of the main target, a rapidly rotating B2V star (HR 6141) was observed at an airmass similar to what was expected for the Bulge star. The featureless spectrum of HR 6141 was used to divide out telluric lines in the bulge star spectrum.

[1] https://it019909.massey.ac.nz/moa/alert/index.html

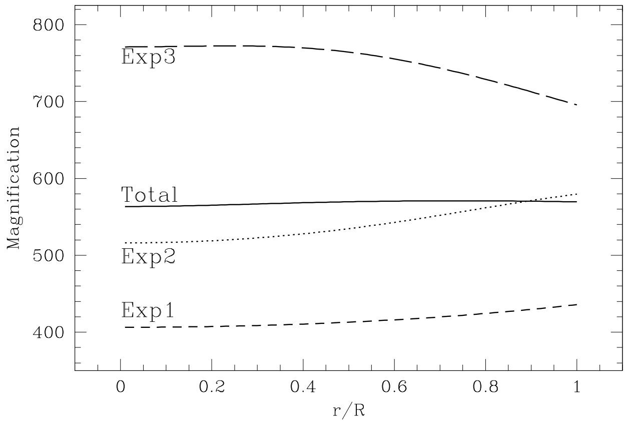

Fig. 1. The magnification profiles during the three UVES exposures of MOA-2010-BLG-285S (dashed and dotted lines), and the total magnification profile when co-adding all three exposures (solid line).

The lens for this event turned out to be in a binary system, and during the observations the source approached very closely to a cusp of the binary-lens caustics. This means that the source star can not be treated as infinitesimally small, and that there may be substantial differential magnification of the source's surface, which in turn could conceivably have an impact on the interpretation of the spectrum. The effect of limb-darkening was investigated by Johnson et al. (2010) who found that the impact of finite source effects on the spectral analysis is typically very small, unless the spectrum is taken when a strong cusp or the caustic lies directly over the source. We have checked the effects on the spectra that we obtained of MOA-2010-BLG-285S. As can be seen in Fig. 1 the magnifications as well as the magnification profiles changed between the three UVES exposures. When adding all three exposures the total magnification is around 550 and almost constant all over the surface of the source. Hence, the effects on the co-added spectrum are negligible.

3. Stellar parameters and line synthesis

Stellar parameters and elemental abundances were determined in the same way as for our previous sample of microlensed dwarf stars in the bulge (see Bensby et al. 2009b, 2010b). Uncertainties in the stellar parameters and abundance ratios have been calculated according to the prescription in Epstein et al. (2010).

The Li abundance was determined through line profile fitting of the ^{7}Li I resonance doublet line at 670.8 nm. This line is highly structured and we have adopted the $\log gf$-values for the different line components from Smith et al. (1998). The calculation of synthetic spectra is done with the Uppsala SPECTRUM software, and our methodology is fully described in Bensby & Feltzing

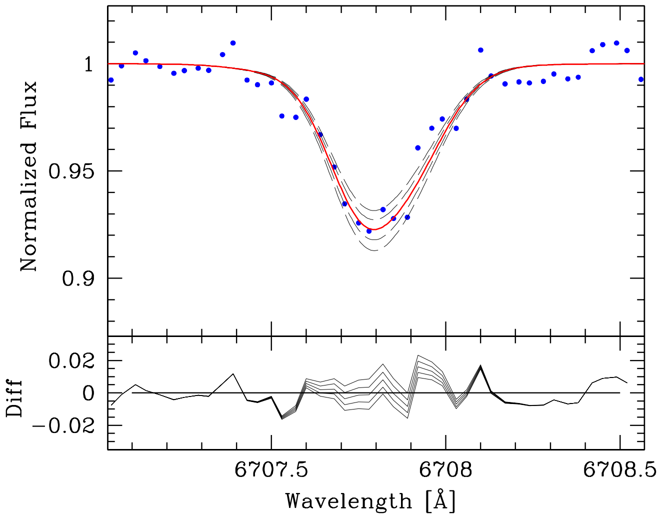

Fig. 2. The Li I line at 670.8 nm in MOA-2010-BLG-285S. The dots are the observed spectrum and the thick solid line the best fit representing an abundance of $\log\epsilon(\text{Li}) = 2.21$. Thin dashed lines represent different Li abundances from 2.15 to 2.27 dex in steps of 0.03 dex. Lower panel shows the differences between the observed and synthetic spectra.

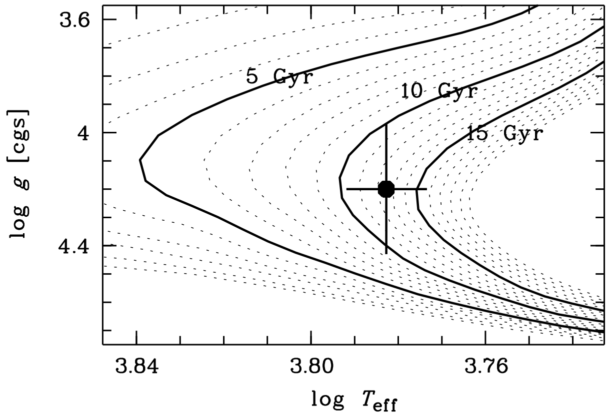

Fig. 3. Y^2 isochrones (Demarque et al. 2004) with [Fe/H] = −1.20 and [α/Fe] = +0.4 that were used to estimate the stellar age.

(2006) where the forbidden [C I] at 872.7 nm was analysed. The difference is that we here analyse a different wavelength region and are therefore using a different line to determine the width of the RAD-TAN profile; here we use the Fe I line at 667.8 nm.

By producing a set of synthetic spectra with different Li abundances, varying in steps of 0.03 dex, we performed a χ^2-minimisation to find the best fitting synthetic spectrum, and hence the Li abundance. The best fitting value is $\log\epsilon(\text{Li}) = 2.21$ (see Fig. 2). According to Lind et al. (2009a) the 1-D non-LTE correction for a star with $T_{\text{eff}}/\log g/[\text{Fe/H}] = 6064/4.2/{-1.23}$ is −0.05 dex for the 670.8 nm line, giving a NLTE corrected abundance of $\log\epsilon(\text{Li}) = 2.16$ for MOA-2010-BLG-285S. We expect that the 3D non-LTE abundance would be quite similar (Asplund et al. 2003; Sbordone et al. 2010).

The uncertainty in the Li abundance has three main sources: the continuum level; the line profile fitting; and the effective temperature. Based on the high quality of the spectrum ($S/N \approx 170$), and also by visual inspection of the spectrum, the uncertainty due to the placement of the continuum was estimated by changing the continuum level by 0.005 and then redoing the fitting. The uncertainty due to the fitting is estimated to be 0.03 dex (see also Fig. 2). Finally we determined a new abundance by changing T_{eff} with 129 K (the 1σ uncertainty, Table 1). Adding the three uncertainties in quadrature (assuming that they are uncorrelated) gives a total error of 0.10 dex.

In the previously published sample of 15 microlensed bulge dwarf stars in Bensby et al. (2010b), we can detect the Li line in some of the stars. However, most of them have effective temperatures well below 5900 K, meaning that much of their initial Li has been destroyed (see Sect. 1). Many of them also have spectra that are of less good quality than that obtained for MOA-2010-BLG-285S, making Li detections even more difficult. Li abundances for some of the stars in Bensby et al. (2010b) will be included in an upcoming publication where we will present an extended sample of microlensed bulge dwarfs from the 2010 campaign.

4. Results and discussion

Table 1 lists the stellar parameters and abundance ratios for MOA-2010-BLG-285S. It is a warm and metal-poor turn-off star with an age of 12.5 ± 3 Gyr as inferred from Y^2 isochrones (Demarque et al. 2004) (see Fig. 3). At [Fe/H] = −1.23 it is also the currently most metal-poor dwarf star known in the Galactic bulge, significantly more metal-poor than the previous record holder OGLE-2009-BLG-076S at [Fe/H] = −0.86 (Bensby et al. 2009a). Its α-element abundances show enhancements of 0.3 to 0.5 dex relative to iron, and the abundances of the iron-peak elements Cr and Ni are (within the error-bars) close to solar (i.e., [Cr, Ni/Fe] ≈ 0). This abundance pattern is consistent with what is seen in thick disk dwarf stars at the same metallicity (e.g., Bensby et al. 2005, 2007; Reddy & Lambert 2008).

MOA-2010-BLG-285S is the first metal-poor dwarf star for which Li has been clearly detected in the Galactic bulge. The Li abundance we find for MOA-2010-BLG-285S, $\log\epsilon(\text{Li}) = 2.16$, is fully consistent with what is seen in other metal-poor dwarf stars in the Galactic disk and halo at this effective temperature and metallicity (see Fig. 4). In Fig. 5 we see that the star lies on the metal-rich end of the Li Spite plateau (Spite & Spite 1982). Combined with its old age, MOA-2010-BLG-285S is an excellent confirmation that the bulge did not undergo a large amount of Li production or astration in its earliest phases.

Furthermore, the Li abundance in MOA-2010-BLG-285S, when coupled with observations in a different galaxy (ω Cen, Monaco et al. 2010) and different components of the Galaxy (halo, (e.g., Meléndez et al. 2006), thick disk, (Molaro et al. 1997), and bulge (this work)), suggests that the Spite plateau is universal. Also, the measured value for MOA-2010-BLG-285S

Table 1. Stellar parameters and abundances for MOA-2010-BLG-285S

[Fe/H] =	−1.23 ± 0.09	[O/Fe] =	+0.52 ± 0.27
T_{eff} =	6064 ± 129 K	[Mg/Fe] =	+0.42 ± 0.07
$\log g$ =	4.20 ± 0.23	[Si/Fe] =	+0.30 ± 0.07
ξ_{t} =	1.85 ± 0.38 km s^{-1}	[Ca/Fe] =	+0.35 ± 0.06
Age=	12.5 ± 3 Gyr	[Ti/Fe] =	+0.38 ± 0.12
$v_{\text{r,heliocentric}}$ =	+46.0 km s^{-1}	[Ni/Fe] =	−0.08 ± 0.11
$\log\epsilon(\text{Li})$ =	2.16 ± 0.10	[Cr/Fe] =	−0.01 ± 0.19
		[Na/Fe] =	−0.05 ± 0.05

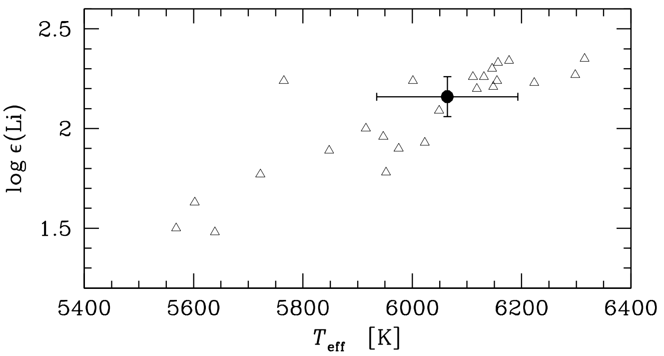

Fig. 4. Comparison of the Li abundance for MOA-2010-BLG-285S (filled circle) with the stars from Meléndez et al. (2010) that have $-1.5 < [\mathrm{Fe/H}] < -1.0$ (open triangles). All abundances have been corrected for non-LTE effects as given by Lind et al. (2009a).

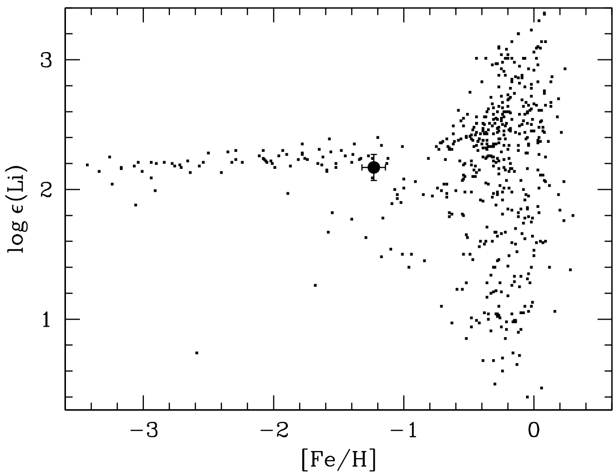

Fig. 5. Li abundance versus [Fe/H]. The filled circle indicates MOA-2010-BLG-285S. Comparison data (small dots) come from Meléndez et al. (2010) and Lambert & Reddy (2004).

is in agreement with models 2, 3, and 4 of Matteucci et al. (1999) that predict negligable production of Li by the ν-process in supernovae, carbon stars and massive AGB stars until $[\mathrm{Fe/H}] > -1$ in the bulge.

5. Summary

In this letter we report the discovery and analysis of the most metal-poor dwarf star in the Bulge exposed to detailed abundance analysis. Had it not been for gravitational microlensing, during which its apparent magnitude was amplified by a factor of about 550, the star would be much too faint to be accessible for high-resolution spectroscopy. According to models of standard stellar evolution, the star should have retained most of its initial Li abundance, which enables us to compare with the predictions from Big Bang nucleosynthesis (BBNS). The only other detections of Li in the Galactic bulge are from observations of RGB and AGB stars (e.g., Gonzalez et al. 2009) in which the atmospheric Li abundance has been altered. Dwarf and subgiant stars with effective temperatures greater than about 5900 K are the only reliable tracers of Li (see discussion above).

Our main results are:

1. At $[\mathrm{Fe/H}] = -1.23$ MOA-2010-BLG-285S is the currently most metal-poor dwarf star in the Galactic bulge. It has an old age of 12.5 ± 3 Gyr and enhanced $[\alpha/\mathrm{Fe}]$ ratios, consistent with those seen in the Galactic thick disk.
2. For the first time, Li has been clearly detected in a metal-poor dwarf star in the Galactic bulge. We find an NLTE corrected Li abundance of $\log\epsilon(\mathrm{Li}) = 2.16$, which is in excellent agreement with Galactic halo and thick disk dwarf stars at the same effective temperature and metallicity, showing that the chemical similarities between the Bulge and other old populations extend also to Li. Its placement on the metal-rich end of the Spite Li plateau indicates that the Bulge did not undergo significant enrichment of Li in its earliest phases.
3. The similar Li abundances found in the bulge, halo, thick disk, and in another galaxy (ω Cen) suggest that the lithium Spite plateau is universal.

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