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Primordial and Pre-Galactic Origins of the Lithium Isotopes

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Abstract.

There are currently two cosmological lithium problems: compared with predictions from Big Bang Nucleosynthesis and models for Galactic cosmic ray production, the observed ${}^7\text{Li}$ abundance in Galactic halo stars is too low while the ${}^6\text{Li}$ content is too high. Here we report on new Keck/HIRES observations of the two extremely metal-poor stars G064-012 and G064-37, which both show distortions of the Li I 670.8 nm line consistent with a significant ($\approx 3\sigma$) presence of ${}^6\text{Li}$. If confirmed, these are the lowest metallicity ${}^6\text{Li}$ detections and would suggest a cosmological or pre-Galactic origin for the isotope. Invoking stellar Li depletion to solve the above-mentioned ${}^7\text{Li}$ discrepancy would further increase the inferred initial ${}^6\text{Li}$ abundance by a factor of ≈ 10 . Possible ${}^6\text{Li}$ production scenarios are decaying/annihilating supersymmetric particles within the first few minutes of the Big Bang and cosmological cosmic rays from the first stars, although stellar flare production can not be ruled out either. Work still remains, however, before one can unequivocally say that ${}^6\text{Li}$ really has been detected in these and other halo stars, in particular whether convective atmospheric motions and non-LTE line formation can mimic the presence of ${}^6\text{Li}$ in the observed line profiles.

Keywords: Stellar atmospheres, stellar spectroscopy, stellar chemical compositions, Galactic halo stars, origin of the elements, Big Bang nucleosynthesis, cosmic ray nucleosynthesis

PACS: 97.10.Ex, 97.10.Tk, 98.35.Bd, 98.80.Ft

INTRODUCTION

The tiny cosmic abundances of the two lithium isotopes are a poor reflection of their great significance in astrophysics and cosmology. Their wide-ranging applications stem from their multitude of production sites as well as their fragility, enabling ${}^6\text{Li}$ and ${}^7\text{Li}$ to trace stellar, galactic and cosmic evolution. In old stars in the Galactic halo, the observed ${}^7\text{Li}$ in their atmospheres has a predominant origin in the Big Bang Nucleosynthesis with a minor contribution from Galactic cosmic ray production that increases with metallicity. ${}^6\text{Li}$ on the other hand is mainly produced by cosmic ray alpha-fusion reactions in the interstellar/-galactic medium as the primordial abundance is negligible, at least in standard versions of Big Bang Nucleosynthesis. The interpretation is complicated, however, by the fact that both isotopes are easily destroyed in stellar interiors when encountering high enough temperatures.

Presently there are two cosmological problems lacking a plausible explanation (Asplund et al. 2006). The first one is well-known (e.g. Spite & Spite 1982; Asplund et al. 2006; Bonifacio et al. 2007), namely that the observed ${}^7\text{Li}$ abundance in halo stars is a factor of about 3-4 lower than predicted from standard Big Bang Nucleosynthesis and the baryon density inferred from the cosmic microwave background (Spergel et al. 2007). The two effects most commonly blamed for this discrepancy, erroneous stellar effective temperatures and stellar Li de-

pletion, can by themselves only be attributed to half of this shortfall given other observational constraints such as the tiny intrinsic cosmic ${}^7\text{Li}$ abundance scatter (e.g. Korn et al. 2006; Meléndez et al. 2006). Furthermore, it still remains to be convincingly demonstrated that these effects do in fact play a significant role at all in solving the Li problems.

More recently, a second cosmological Li problem has been uncovered in the sense that the observed ${}^6\text{Li}$ abundance at the lowest metallicities is too high to be explained by standard Galactic cosmic ray production (Asplund et al. 2006). Several possibilities have been proposed for additional ${}^6\text{Li}$ production during the early phases of the Universe, either through supersymmetric particles, cosmological cosmic rays or stellar flares (e.g. Jedamzik 2004a,b; Rollinde et al. 2006; Tatischeff & Thibaud 2006).

Here we present a preliminary analysis of new Keck/HIRES observations of additional halo stars. In particular, the two most metal-poor stars, G064-012 and G064-037, with $[\text{Fe}/\text{H}] \leq -3.0$ show evidence for detectable ${}^6\text{Li}$ at the similar high abundance as in our previous VLT/UVES observations. Some possible implications of these new results are discussed together with some caveats to these extraordinarily challenging observations and analyses.

TABLE 1. Achieved signal-to-noise, adopted stellar parameters and derived Li isotopic abundances for the Keck/HIRES spectra

Star	S/N	T_{eff}	$\log g$	[Fe/H]	$\log \epsilon_{\text{Li}}$	${}^6\text{Li}/{}^7\text{Li}$
HD84937	830	6293	4.07	-2.11	2.16	0.051 ± 0.015
HD140283	1110	5753	3.70	-2.40	2.09	0.017 ± 0.010
G064-012	860	6371	4.26	-3.24	2.16	0.059 ± 0.021
G064-037	560	6368	4.37	-3.08	1.97	0.111 ± 0.032

OBSERVATIONS AND ANALYSIS

We have employed the HIRES instrument on the Keck-I 10m telescope to extend our previous successful observing campaign on VLT (Asplund et al. 2006) to determine the Li isotopic abundances in Galactic halo stars. Some 10 stars were observed during three separate runs in 2005 and 2006. Here we present an analysis of four of those: G064-012 ([Fe/H] = -3.2), G064-037 ([Fe/H] = -3.1), HD140283 ([Fe/H] = -2.4) and HD84937 ([Fe/H] = -2.1). The latter two have previously been examined for ${}^6\text{Li}$ using a variety of telescopes and spectrographs (e.g. Smith et al. 1993; Cayrel et al. 1999; Aoki et al. 2004; Asplund et al. 2006) and thus serve as an important control sample. The observed Keck/HIRES spectra have a spectral resolving power of $\lambda/\Delta\lambda \approx 90,000 - 100,000$ and signal-to-noise of $S/N \approx 550 - 1100$ per pixel around the Li I 670.8 nm line. Only such high-quality spectra allow the determination of the expected small ${}^6\text{Li}/{}^7\text{Li}$ ratios using the isotopic shift of the Li line.

Our analysis proceeded in the same manner as in our VLT study (Asplund et al. 2006). In particular we have employed both 1D hydrostatic MARCS model atmospheres and 3D hydrodynamical simulations of stellar surface convection (Asplund 2005 and references therein). The adopted stellar parameters were based on hydrogen Balmer lines for T_{eff} , parallaxes and isochrones for $\log g$ and Fe II lines for [Fe/H] (Nissen et al. 2007). The T_{eff} for G064-012 and G064-037 would have been 159 and 272 K, respectively, higher had we instead employed photometric colours based on the infrared flux method calibration of Meléndez et al. (2006), which would have resulted in 0.11 and 0.19 dex, respectively, higher Li isotopic abundances.

Since the presence of ${}^6\text{Li}$ manifests itself as a slightly increased line broadening and asymmetry of the Li I 670.8 nm line, it is critical to determine the intrinsic line shapes due to convective motion and stellar rotation from lines of other species. Here we have utilised > 20 lines of Ca I, Cr I, Fe I, Fe II, Mg I, Sc II and Ti II of similar strengths as the Li line. This is a significant improvement over the typically five lines employed in Asplund et al. (2006), which result in a corresponding improvement in the estimates of the macroturbulence ζ_{macro} (1D)

and rotation $v_{\text{rot}} \sin i$ (3D). For the χ^2 -analysis, the total Li abundance, the ${}^6\text{Li}/{}^7\text{Li}$ ratio, the continuum placement and the wavelength zero-point were allowed to vary. The quoted errors in the derived isotopic ratios given in Table 1 factor into the uncertainties stemming from the finite S/N, broadening and stellar parameters. The values given here are based on our 1D analysis, although the 3D LTE results in terms of ${}^6\text{Li}/{}^7\text{Li}$ are very similar. We know, however, that in 3D there will be significant departures from LTE for Li (Asplund et al. 2003). Whether departures from LTE in 3D may impact the estimated ${}^6\text{Li}/{}^7\text{Li}$ ratios (Cayrel et al. 2007) will be discussed further below.

Our Keck spectra confirm the measured ${}^6\text{Li}/{}^7\text{Li}$ for HD140283 and HD84937 from previous studies (Smith et al. 1993; Cayrel et al. 1999; Aoki et al. 2004; Asplund et al. 2006), which lends confidence to our observations, data reduction and analysis procedures. Our value for HD84937 is essentially identical to that of Cayrel et al. but with a slightly smaller error: ${}^6\text{Li}/{}^7\text{Li} = 0.051 \pm 0.015$ (1 σ). The estimated ${}^6\text{Li}$ is non-zero in HD140283 but no significant detection can be claimed as was also the case in our VLT/UVES analysis (Asplund et al. 2006).

More noteworthy, we seem to detect ${}^6\text{Li}$ in both G064-012 and G064-037 at a significant level ($\approx 3\sigma$): ${}^6\text{Li}/{}^7\text{Li} = 0.059 \pm 0.021$ and $= 0.111 \pm 0.035$, respectively. Fig. 1 shows the fit of the Fe I 426 nm and the Li I 670.8 nm line profiles. These two stars are the lowest metallicity stars in which ${}^6\text{Li}$ has been positively identified, a factor of > 2 lower metal-content than in LP815-43 with [Fe/H] = -2.7 (Asplund et al. 2006). As such, our new observations are of particular importance. We note that Inoue et al. (2005) claimed a detection of ${}^6\text{Li}$ in G064-012 at a similar abundance level to ours based on a somewhat inferior quality Subaru-spectrum compared with our Keck observations. Subsequent analysis by this group, however, have revealed that their initial result may not be significant (W. Aoki, 2006, private communication). The full details of this work have however not yet appeared and we can thus not comment further on it.

In terms of abundances, the ${}^6\text{Li}/{}^7\text{Li}$ ratios correspond to $\log \epsilon_{\text{Li}} = 0.93 \pm 0.15$ and 1.02 ± 0.13 for G064-012 and G064-037, respectively. These values are the 1D non-LTE results, in which the recent collisional data of Barklem et al. (2003) have been taken into account

FIGURE 1. *Left panel:* The observed Fe I 426 nm line in G064-012 (rhombs) together with the best-fitting 1D (dashed, red) and 3D (solid, blue) profiles. Notice the much reduced residuals in the 3D case due to the predicted line asymmetry. *Right panel:* The observed and predicted (1D) profiles of the Li I 670.8 nm line for three different ${}^6\text{Li}/{}^7\text{Li}$ ratios. The best-fitting value is ${}^6\text{Li}/{}^7\text{Li} \approx 5\%$.

($\Delta \log \epsilon_{\text{Li}} = -0.07$ dex). These values do not include the expected pre-main sequence ${}^6\text{Li}$ depletion, which is ≈ 0.3 dex for these stars (Richard et al. 2005; Asplund et al. 2006).

IMPLICATIONS

Fig. 2 shows our derived Li isotopic abundances for our Keck sample together with the corresponding results from our VLT survey (Asplund et al. 2006). The by now well-known $\approx 0.5 - 0.6$ dex difference between the observed and predicted ${}^7\text{Li}$ abundance from standard Big Bang Nucleosynthesis is obvious. Asplund et al. (2006) found that the cosmic ${}^7\text{Li}$ abundance scatter is vanishingly small although the two otherwise similar stars G064-012 and G064-037 analysed here appear to show real differences in their ${}^7\text{Li}$ content. The reality of the trend with $[\text{Fe}/\text{H}]$ for ${}^7\text{Li}$ is still hotly debated but could for example reflect cosmic ray production, metallicity-dependent Li depletion or simply shortcomings in the analysis (e.g. 3D non-LTE effects, erroneous T_{eff}). There may even be indications of a steeper slope at the lowest $[\text{Fe}/\text{H}]$ (Asplund et al. 2006) or increased intrinsic ${}^7\text{Li}$ abundance variations below $[\text{Fe}/\text{H}] \approx -3$ (Bonifacio et al. 2007). The predicted ${}^7\text{Li}$ depletion is negligible (≤ 0.03 dex for $T_{\text{eff}} \geq 6000$ K) in standard stellar models but other mechanisms such as rotationally-induced mixing or turbulent diffusion (e.g. Richard et al. 2005) have been invoked to bridge the ${}^7\text{Li}$ discrepancy (e.g. Korn et al. 2006). It is questionable whether the very small intrinsic scatter can be retained for such large depletion factors but of course ${}^7\text{Li}$ destruction can still be partly to blame if not the entire solution.

If confirmed, our new Keck observations push the detections of ${}^6\text{Li}$ to yet lower metallicity compared with previous work (Smith et al. 1993; Cayrel et al. 1999; Asplund et al. 2006). At $[\text{Fe}/\text{H}] \leq -3.0$, no measurable quantity of ${}^6\text{Li}$ is expected from models of Galactic cosmic ray production, yet we apparently find it at a level of ${}^6\text{Li}/{}^7\text{Li} \approx 5 - 10\%$ or $\log \epsilon_{\text{Li}} \approx 1.0$ in G064-012 and G064-037. Compared with the typical model of Prantzos (2006) shown in Fig. 2, the observed ${}^6\text{Li}$ abundance is a factor of ≈ 30 higher. When taking into account the expected pre-main sequence ${}^6\text{Li}$ depletion the initial ${}^6\text{Li}$ abundance was (at least) another 0.3 dex higher (Richard et al. 2005; Asplund et al. 2006). Furthermore, if ${}^7\text{Li}$ has been destroyed by some non-standard mechanism by the required $\approx 0.5 - 0.6$ dex mentioned above the corresponding ${}^6\text{Li}$ depletion would be significantly greater and result in an original abundance of $\log \epsilon_{\text{Li}} \geq 2.0$. In Fig. 2 only the standard ${}^6\text{Li}$ depletion of ≈ 0.3 dex has been taken into account. While the ${}^6\text{Li}$ abundances then increase for $[\text{Fe}/\text{H}] \geq -1.5$, at lower metallicities the observations seem to suggest the presence of a ${}^6\text{Li}$ plateau. The new Keck results certainly strengthen this conclusion.

If Galactic cosmic ray spallation and alpha-fusion reactions are insufficient for producing the high observed ${}^6\text{Li}$ abundance already during the early phases of the Galaxy, what can then be the origin? Several suggestions have been put forward, all plausible, but unfortunately all still requiring several free parameters in their quantitative modelling. It may be possible to achieve $\log \epsilon_{\text{Li}} \approx 1.0$ through flares on the stars themselves (Tatischeff & Thibaud 2006) but it would require that the metal-poor stars were very rapidly rotating and magnetically active although no such empirical evidence exists, quite on the

FIGURE 2. *Left panel:* the observed ${}^7\text{Li}$ (triangles) and ${}^6\text{Li}$ (stars, circles and squares) abundances from Keck (red, present work) and VLT (blue, Asplund et al. 2006). The horizontal line denote the predicted primordial ${}^7\text{Li}$ abundance from standard Big Bang Nucleosynthesis and the baryon density inferred from the cosmic microwave background. The other solid line represents the expected ${}^6\text{Li}$ abundance from a model of the Galactic cosmic ray production (Prantzos 2006). *Right panel:* Same but including the predicted pre-main sequence depletion of ${}^6\text{Li}$ (Richard et al. 2005).

contrary.

Another proposed scenario invokes cosmological cosmic rays, either from shocks arising during structure formation (Suzuki & Inoue 2002) or from the first generation of stars (Prantzos 2006; Rollinde et al. 2006). The former is less likely since the required massive dark matter halos are not in place at such early times. The latter model however also faces problems with the required energetics, in particular when considering the (standard) ${}^6\text{Li}$ depletion.

The final possibility is for ${}^6\text{Li}$ production during the era of Big Bang Nucleosynthesis through the decay or annihilation of various postulated supersymmetric particles like the gravitino or neutralino (e.g. Jedamzik 2004a,b). Indeed, there are particular combinations of particle life-times and masses (such as a ~ 80 GeV gravitino) that may simultaneously result in large ${}^6\text{Li}$ production and reduce the ${}^7\text{Li}$ abundance to within the observational range (e.g. Bird et al. 2007). It remains to be seen whether these putative particles are realised in nature with the necessary properties.

HAS ${}^6\text{Li}$ REALLY BEEN DETECTED?

Before drawing too widely-reaching conclusions based on our apparent detection of ${}^6\text{Li}$ in extremely metal-poor stars, it is important to bear in mind how extraordinarily challenging both the observations and the analysis really are. The distortions of the $\text{Li I } 670.8$ nm line introduced by the presence of ${}^6\text{Li}$ are minute and could, in principle at least, be mimicked by shortcomings in the observations, data reduction and analysis. Asplund et al. (2006)

discussed a long list of potential sources of uncertainties and carefully tried to estimate their potential impact on the derived results without identifying any significant systematic errors. One lingering worry though is whether stellar atmospheric velocity fields and departures from LTE could affect the analysis. In the case of the Sun, similar 3D hydrodynamical model atmospheres as applied here can very accurately predict the observed line shifts and asymmetries (e.g. Asplund 2005). This may suggest that our results are indeed trustworthy, since as mentioned above the ${}^6\text{Li}/{}^7\text{Li}$ ratios determined by means of a 3D LTE analysis are very similar to our here preferred 1D non-LTE values. To confirm this, however, will require full 3D non-LTE calculations.

Furthermore, Smith et al. (2001) found that the observed line asymmetries are insufficient to explain the measured ${}^6\text{Li}/{}^7\text{Li}$, at least not for HD84937. More recently, however, Cayrel et al. (2007) arrived at the opposite conclusion based on a study of empirical line asymmetries and 3D computations for the metal-poor turn-off star HD74000. They found that, while a 1D analysis using normal symmetric line profiles resulted in ${}^6\text{Li}/{}^7\text{Li} = 0.024$ (no errors given), when instead employing empirically determined asymmetric profiles the value was -0.028 . Similarly, their results for both 3D LTE and 3D non-LTE implied ${}^6\text{Li}/{}^7\text{Li} \approx 0.00$. This may then suggest by extension that all ${}^6\text{Li}/{}^7\text{Li}$ ratios inferred from an 1D analysis are overestimates, including those presented herein. In this context, it is worth mentioning that most of the stars studied by Asplund et al. (2006) seemed to have some level of ${}^6\text{Li}$ even if it was insufficient to claim a 2σ detection: ${}^6\text{Li}/{}^7\text{Li} \approx 0.01$. Is this also merely a reflection

of systematic errors in 1D analyses?

If confirmed the results of Cayrel et al. would obviously be of great importance since it may then eliminate the need to invoke significant primordial or pre-Galactic ${}^6\text{Li}$ production. The different conclusion reached from empirical line profiles compared with Smith et al. (2001) deserves further investigations but the most significant argument against the analysis of Cayrel and collaborators is how they estimated ${}^6\text{Li}/{}^7\text{Li}$. They tried to infer everything from the Li line itself, including the intrinsic line broadening. As discussed in Asplund et al. (2006), not using the important information available in other lines from different species is an inferior method compared with the one adopted by us. Furthermore, in their 3D analysis Cayrel et al. arbitrarily assumed $v_{\text{rot}} \sin i = 1.0 \text{ km s}^{-1}$ but found it necessary to invoke additional (Gaussian) broadening, which however should not be necessary once $v_{\text{rot}} \sin i$ is well-determined (Asplund 2005). It should also be emphasised that their 3D non-LTE analysis yielded slightly *higher* ${}^6\text{Li}/{}^7\text{Li}$ than their corresponding 3D LTE calculations. If this is a general feature for metal-poor turn-off stars, then our 3D LTE-based values presented here and in Asplund et al. (2006) should not be overestimates but rather *underestimates* and further strengthen our conclusion that ${}^6\text{Li}$ is indeed present in G064-012 and G064-037. It is clearly of utmost importance to carry out 3D non-LTE line formation calculations, not only for Li but also for the calibration lines of Ca, Fe, etc., before reliable conclusions can be drawn regarding the presence or not of ${}^6\text{Li}$ in very metal-poor halo stars. We are currently tackling this daunting challenge.

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