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DETECTION OF THE Li I λ6104 TRANSITION IN THE POPULATION II STAR HD 140283[1]

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ABSTRACT

Lithium is one of the few primordially produced elements. The value of the primordial Li is taken to be that observed in metal-poor dwarfs, where it is not contaminated by stellar Li sources that act on longer timescales. The atmospheric abundance is currently derived from the Li I λ6707 resonance transition, and the validity of the models employed has been questioned (Kurucz). In this Letter, we report the first detection of the Li I λ6104 $2\,^2P$–$3\,^2D$ subordinate transition in the prototype Population II star HD 140283. The same Li abundance of (Li/H) = 1.4×10^{-10} is found to be consistent with both the resonance and subordinate lines. The two lines form at different depths in the atmosphere, implying that the one-dimensional, homogeneous atmospheric models used in the abundance determination are essentially correct. When coupled with the standard big bang yields, the Li in the halo dwarfs provides two solutions for the baryon-to-photon ratio $\eta_{10} = n_b/n_\gamma \times 10^{10}$ and for the present baryon density $\Omega_b h_{70}^2 = 0.0748\eta_{10}$: a first solution at $\eta_{10} \approx 1.8$, which is consistent with the η_{10} implied by the high deuterium values D/H $\approx 2 \times 10^{-4}$ observed in some quasar absorption systems (Webb et al.); and a second solution at $\eta_{10} \approx 4$, which is consistent, within the errors, with the low deuterium D/H = 3.4×10^{-5} measured in other quasar absorption systems (Burles & Tytler).

Subject headings: cosmology: observations — line: formation — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: individual (HD 140283) — stars: Population II

1. INTRODUCTION

Lithium, together with D, ^{3}He, and ^{4}He, is one of the few elements produced by nuclear reactions in the first minutes after the big bang (Wagoner, Fowler, & Hoyle 1967). The observations of these elements and their extrapolation to the primordial values are consistent with the predictions of the standard primordial nucleosynthesis, which provides, together with the relic radiation and the expansion of the universe, robust support for the big bang theory. Recently, additional support for the primordial nature of Li in halo dwarfs has come from the observations of Li in metal-poor stars of the thick disk (Molaro, Bonifacio, & Pasquini 1997). This population is chemically and kinematically distinct from that of the halo, but it has the same Li abundance as the halo. Minniti et al. (1997) claimed detection of Li, at the plateau level, in a metal-rich, but old, star belonging to the Galactic bulge. Finally, Li at the plateau level has also been detected in a star that was possibly born in an external galaxy and then accreted by the Milky Way (Molaro 1997).

So far, the Li abundance always has been obtained only from the analysis of the Li I λ6707 resonance doublet. This is not a very comfortable situation in light of the importance of the determination of lithium abundances in stars for primordial nucleosynthesis, stellar structure, and chemical evolution.

Our ability to determine the Li abundance using simple plane-parallel, homogeneous atmospheres has been recently debated (Kurucz 1995; Kiselman 1997; Gadun & Pavlenko 1997). The analysis of several lines, which sample different depths in the stellar atmosphere, is crucial to test the correctness of the modeling. The one-dimensional, homogeneous, static models that are currently employed may raise concern because they ignore the fine-structure and hydrodynamic phenomena such as granulation, which are seen on the Sun.

The Li I λ6707 resonance transition is the only one readily available to spectroscopic observation. The strongest subordinate line at 6104 Å is much fainter and is blended with an Fe I line and has been detected so far only in young T Tauri stars (Hartigan et al. 1989) and Li-rich giants (Merchant 1967; Wallerstein & Sneden 1982), where Li is more than about 1 dex more abundant owing to the Galactic Li production.

In this Letter, we report the detection of the Li I λ6104 transition in the spectrum of the metal-poor star HD 140283. Both this line and the resonance line are consistent with the computations made using a one-dimensional, homogeneous model atmosphere, thus increasing our confidence that this model represents a satisfactory average of the complex fine structure expected in metal-poor stars.

The use of Li that is observed in halo dwarfs as an indicator of primordial abundance rests on the absence of any Li depletion. Depletion is predicted by nonstandard models that take into account rotational mixing (Pinsonneault, Deliyannis, & Demarque 1992) or diffusion (Vauclair & Charbonnel 1995), but these models predict a downturn of the hot side of the Li plateau and considerable dispersion. It seems that neither the downturn nor the large dispersion is present in the observations, which suggests that diffusion or rotational mixing does not affect significantly the Li observed at the stellar surface of metal-poor dwarfs. However, the downturn can be very small (≈0.2 dex) for the purely diffusive case and a suitable choice of the mixing length parameter ($\alpha = 1.5$; see Deliyannis, Demarque, & Kawaler 1990), and the issue of intrinsic dispersion remains rather controversial, with some positive claims. Ryan et al. (1996) identify a triplet of stars (G064-012, G064-037, CD −33° 1173) with similar colors but Li abundances that are different by a factor of 2.5. Then there is the case of star BD +23°3912, which has an [Fe/H] ≈ −1.3 to −1.5 and a Li abundance that is about 0.20–0.36 dex higher than the plateau (Rebolo, Molaro, & Beckman 1988; King, Deliyannis, & Boesgaard 1996). Moreover, Boesgaard et al. (1998) find differences

[1] Based on observations collected at the European Southern Observatory, La Silla, Chile (proposal 59.E-0350).

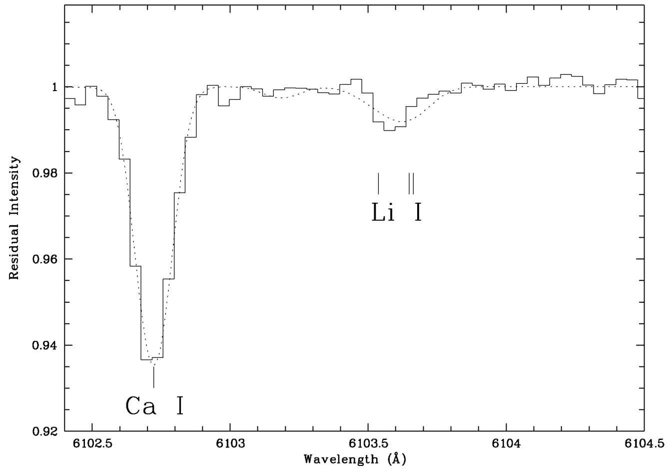

FIG. 1.—Observed Li I 2 ^2P–3 ^2D transition (*solid line*) and the synthetic spectrum (*dotted line*), computed with the parameters $T_{\rm eff}$ = 5691, log g = 3.35, [Fe/H] = −2.5, and (Li/H) = 1.4 × 10^{-10}.

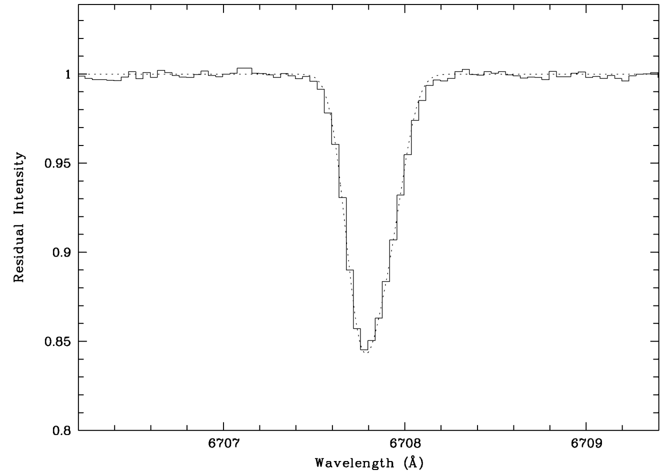

FIG. 2.—Observed Li I 2 ^2S–2 ^2P resonance transition (*solid line*) and the synthetic spectrum (*dotted line*), computed with the parameters given for Fig. 1.

of up to ≈0.5 dex among seven subgiants of M92, but the same objects show other chemical peculiarities, namely, [Mg/Fe] is 0.55 dex lower and [Na/Fe] is 0.76 dex larger than in HD 140283 (King et al. 1998).

2. OBSERVATIONS AND ANALYSIS

We observed HD 140283 on 1997 August 10 and 11 at La Silla, Chile, with the ESO New Technology Telescope and the ESO Multimode Instrument spectrograph under subarcsecond seeing conditions. The high incidence angle echelle grating (tan θ = 4) and a projected slit width of 0″.8 provided a resolution of $\lambda/\Delta\lambda \approx$ 61,000, as measured from the Th lamp emission lines in the region around 6104 Å. The spectra were reduced in a standard way and then co-added, yielding a signal-to-noise ratio of ≈360. The co-added spectrum was normalized by fitting a spline through points determined by averaging the spectrum over continuum windows identified with spectrum synthesis. Figure 1 shows the region around the Li I 2 ^2P–3 ^2D λ6104 transition.

The Li I feature is clearly detected at 6103.6 Å, redward of the Ca I λ6102.723 line. The equivalent width of the feature is 1.8 ± 0.3 mÅ, and the detection is at the 6 σ confidence level.

In Figures 1 and 2, the Li I λ6104 and Li I λ6707 doublets are shown superposed on synthetic spectra. The synthetic spectra were computed using the SYNTHE code (Kurucz 1993), assuming a Li abundance (Li/H) = 1.4 × 10^{-10} (Bonifacio & Molaro 1997), not derived from present data. The model atmosphere for HD 140283 is the same used in Bonifacio & Molaro (1997) and has parameters $T_{\rm eff}$ = 5691, log g = 3.35, [Fe/H] = −2.5, and a microturbulent velocity of ξ = 1 km s^{-1}. This iron abundance is close to the value derived by King et al. (1998), who find [Fe/H] = −2.58, with an effective temperature ($T_{\rm eff}$ = 5650) close to ours. The synthetic spectra were broadened with a Gaussian instrumental point-spread function of 5 km s^{-1}, derived from the Th-Ar lines, and then with a rotational profile of 4 km s^{-1}, derived from the Li I λ6707 resonance line. The subordinate transition was synthesized as three lines, 2 $^2P_{1/2}$–3 $^2D_{3/2}$, 2 $^2P_{3/2}$–3 $^2D_{5/2}$, and 2 $^2P_{3/2}$–3 $^2D_{3/2}$. The corresponding wavelengths (Martin & Wiese 1976), marked in Figure 1 as vertical bars, and log gf-values (Lindgård & Nielsen 1977) are 6103.538 Å, 0.101; 6103.649 Å, 0.361; and 6103.664 Å, −0.599.

3. DISCUSSION

The Li I line-forming regions lie in the upper part of the atmospheric convective zone, where Li is mostly ionized as a result of its low-ionization potential. This is why the precise determination of Li abundances requires accurate observations, an accurate stellar effective temperature, and an appropriate modeling of the atmosphere of a metal-poor star. The model atmospheres employed are one dimensional, with plane-parallel geometry, and ignore any inhomogeneity effect, such as granulation. Qualitative computations, based on a two-stream model atmosphere, suggested that the abundance of Li in halo dwarfs could be underestimated by as much as a factor of 10 (Kurucz 1995), but more recent calculations based on two-dimensional (Gadun & Pavlenko 1997) and three-dimensional (Kiselman 1997) atmospheric models show that the effects of granulation on the Li I lines are much less important. Granulation effects in the atmosphere have a depth dependence, and this should produce different effects in the resonance and subordinate doublets.

As can be seen from Figures 1 and 2, the same Li abundance reproduces satisfactorily both the λ6104 and λ6707 doublets. The two transitions form at different depths in the stellar atmosphere: unit optical depth at wavelength 6707.761 Å is attained at log ($\tau_{\rm Ross}$) ≈ −0.57, corresponding in our model to a local temperature of 5235 K, while at wavelength 6103.649 Å, it is already attained at log ($\tau_{\rm Ross}$) ≈ −0.09, or T = 5915 K. The resonance line receives contributions from a more extended region than the subordinate line. Unit optical depth at the wavelength at which the residual intensity is 0.999 is attained at log ($\tau_{\rm Ross}$) ≈ −0.11 for the resonance line but at log ($\tau_{\rm Ross}$) ≈ −0.08 for the subordinate line. Thus, the subordinate line samples deeper and hotter layers than the resonance line, as shown in Figure 3.

The lower level of the Li λ6104 transition is the upper level of the λ6707 2 ^2S–2 ^2P transition. Our synthetic spectra are computed under the LTE assumption, and the consistency between the two lines implies a correct computation of the populations of the 2S, 2P, and 3D levels. This is in agreement with

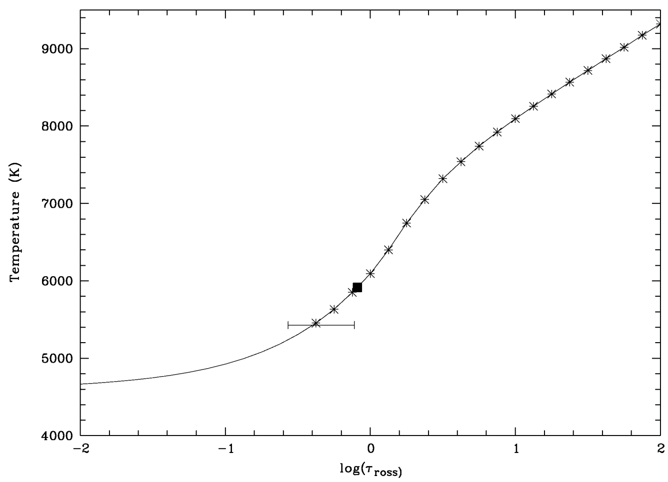

FIG. 3.—Temperature structure of our model atmosphere for HD 140283, as function of the Rosseland optical depth. The asterisks indicate the convective layers. The horizontal line marks the depths at which the monochromatic optical depth $\tau_\lambda = 1$, across the profile of the Li I λ6707 line. The square symbol marks the depth at which $\tau_{6103.649} = 1$, the range over which unit optical depth is attained across the profile of the subordinate line is smaller than the size of the symbol.

the theoretical estimations, which predict relatively small corrections for non-LTE effects in the Li λ6707 line (Carlsson et al. 1994; Pavlenko & Magazzù 1996). Thus, the detection of a subordinate Li I line, and its consistency with the abundance derived from the resonance λ6707 doublet, provides support to the correctness of this Li abundance.

The consistency of the abundances based on the Li I λ6707 and λ6104 transitions observed in HD 140283 supports the Li abundances measured in the Population II stars, using one-dimensional model atmospheres, in the last decades. The new generation of large telescopes will allow us to measure the Li λ6104 Li I subordinate doublet in other, much fainter, Population II stars, thus permitting us to verify this consistency on the grounds of a statistically significant sample and ultimately to achieve a more accurate measurement of the primordial Li abundance.

Among the light elements produced in the first minutes after the big bang, Li is the only one that shows a nonmonotonic behavior with η_{10}, the so-called Li valley, which reflects the different nuclear reactions that synthesize Li at different baryonic densities. The most recent measurement of the Li primordial abundance is (Li/H) = $(1.73 \pm 0.05_{stat} \pm 0.2_{sys}) \times 10^{-10}$ (Bonifacio & Molaro 1997), which is the mean value of 41 halo stars for which precise effective temperatures, determined by means of the infrared flux method (Alonso, Arribas, & Martinez-Roger 1996), were available. The systematic errors, which dominate the error budget, come from a possible offset of ± 75 K in the zero point of the temperature scale of cool stars. This Li abundance intercepts the primordial yields for two different values of η_{10}, which unfortunately do not help in resolving the deuterium and helium controversies. Each solution for η_{10} obtained from Li is consistent with either the high-deuterium/low-helium combination (Webb et al. 1997; Olive, Steigman, & Skillman 1997) or the low-deuterium/high-helium combination (Burles & Tytler 1998; Izotov, Thuan, & Lipovetsky 1997). The lower η_{10} requires considerable D destruction to match the presently observed abundance in the local interstellar medium of the Galaxy. The higher η_{10} value is also consistent with the low deuterium abundance [D/H = $(3.9 \pm 1) \times 10^{-5}$] derived from the 92 cm hyperfine transition emission toward the unprocessed Galactic anticenter (Chengalur, Braun, & Butler Burton 1997).

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