DETAILED ANALYSIS OF NEARBY BULGELIKE DWARF STARS. II. LITHIUM ABUNDANCES

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ABSTRACT

Li abundances are derived for a sample of bulgelike stars with isochronal ages of 10–11 Gyr. These stars have orbits with pericentric distances, $R_p$, as small as 2–3 kpc and $Z_{max} < 1$ kpc. The sample comprises G and K dwarf stars in the metallicity range $-0.80 \leq [\text{Fe}/\text{H}] \leq +0.40$. Few data on Li abundances in old turnoff stars ($\geq 4.5$ Gyr) within the present metallicity range are available. M67 (4.7 Gyr) and NGC 1818 (6 Gyr) are the oldest studied metal-rich open clusters with late-type stars. Li abundances have also been studied for a few samples of old metal-rich field stars. In the present work, a high dispersion in Li abundances is found for bulgelike stars with all metallicity ranges, comparable with values in M67. The role of metallicity and age on a Li depletion pattern is discussed. The possible connection between Li depletion and oxygen abundance due to atmospheric opacity effects is investigated.

Subject headings: Galaxy: abundances — stars: abundances — stars: evolution — stars: late-type

1. INTRODUCTION

Lithium is a key element in astrophysics. The inference of the original lithium abundance in the universe should provide the cosmic ratio of baryons to photons at primordial times and constrain the standard model of big bang nucleosynthesis. Li is destroyed in stars by $^7\text{Li}(p,\alpha)^4\text{He}$ reactions at $T \geq 2.5 \times 10^6$ K. On the other hand, different sources of Li, besides the primordial nucleosynthesis, have been proposed: novae, asymptotic and red giant branch stars, C stars and Type II SNe, and spallation of C, N, and O elements by Galactic cosmic rays in the interstellar medium. To infer the primordial Li abundance, an overall understanding of the different destruction/production mechanisms and their rates is required.

In a classical work, Spite & Spite (1982) detected an almost uniform Li abundance in halo stars. This Li plateau, with $A(\text{Li}) \sim 2.1$, is constant for all metal-poor stars within the temperature range $5700 \text{K} \leq T_{\text{eff}} \leq 6300$ K. Many authors consider this value as the primordial Li abundance of the protogalactic cloud. Others claim that it is depleted by about 0.2–0.3 dex from the primordial value. (For recent reviews, see Cayrel 1998; Spite, Spite, & Hill 1998; Pinsonneault, Charbonnel, & Deliyannis 2000.)

Solar system observations led to meteoritic Li abundances of $A(\text{Li}) \sim 3.3$ (Grevesse, Noels, & Sauval 1996). T Tauri stars provided a similar value, $A(\text{Li}) \sim 3.2$ (Magazzú, Rebolo, & Pavlenko 1992), and pre-MS stars in the Orion Nebula provided values of $A(\text{Li}) \sim 3.6$ (King 1993) and $A(\text{Li}) \sim 3.2$ (Cunha, Smith, & Lambert 1995). These observations show that there is a roughly constant galactic interstellar medium (ISM) abundance. If the Li plateau value is the actual primordial value, the ISM abundance is enhanced by a factor of 10. Therefore, the understanding of the galactic Li history demands a complete theory of stellar evolution and their contribution to the ISM enrichment.

Standard models, which have successfully explained stellar evolution and H-R diagrams, predict that convection is the only mechanism that rules Li depletion in low-mass stars. In these models, Li depletion is a function of stellar mass, metallicity, and age (e.g., D’Antona & Mazzitelli 1984; Proffitt & Michaud 1989).

Open clusters are natural targets to probe these models because they have stellar contents of high metallicity sampling an evolutionary sequence. However, their study revealed a more complex picture than that outlined by standard models. MS depletion is expected to occur only in the lower mass ($M < 0.9 M_\odot$) stars. But observations indicate that a depletion mechanism acts during the entire MS lifetime even in stars where the temperature at the bottom of the convective zone (CZ) is not high enough to burn Li. In addition, stars with the same age, composition, and mass show dispersions in $A(\text{Li})$ as high as 1.5 dex (e.g., Soderblom et al. 1993a for Pleiades late-G and early-K stars; Pasquini, Randich, Pallavicini 1997 for M67).

Nonstandard models with different depletion mechanisms have been suggested to account for the observations: mixing driven by angular momentum loss, microscopic diffusion, internal wave diffusion, differential rotation, and depletion by MS mass loss (see Pinsonneault 1997; Deliyannis, Pinsonneault, & Charbonnel 2000; Pinsonneault et al. 2000). None of these models provided a satisfactory fit to observations alone, indicating that two or more mechanisms are acting together.

A comprehensive literature is available for lithium in open clusters. In the last two decades, several groups observed and derived Li abundances for several open clusters solar-type stars. Some examples of studied young clusters are Blanco I (Jeffries 1997), $\alpha$ Per (Boesgaard et al. 1998), and NGC 6811 (Mouwai and D’Antona 1998).

$A(\text{Li}) = \log \epsilon(\text{Li}) = \log \left( N(\text{Li}) / N(\text{H}) \right) + 12$. 

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5500 K are observed in these clusters in the temperature range 5300 K to 5800 K. M34 (Jones et al. 1997), NGC 6475 (James & Jeffries 1997) with 200–300 Myr and NGC 6633 (Jeffries 1997), Hyades (Thornburn 1993; Soderblom et al. 1995) and Praesepe (Soderblom et al. 1993c) with 600–800 Myr are young clusters with stars of relatively short evolution time spent in MS. NGC 754 (Hobbs & Pilachowski 1986), IC 4651, and NGC 3688 (Randich, Pasquini, & Pallavicini 2000), with ~2 Gyr, are intermediate-age clusters. These groups show decreasing Li abundances with age.

Few data are available for old stars in open clusters or in the field for the present metallicity (~0.80 ≤ [Fe/H] ≤ +0.40) and temperature (4700 K ≤ T eff ≤ 5900 K) ranges. M67 (Pasquini et al. 1997; Jones et al. 1999) and NGC 188 (Hobbs & Pilachowski 1988), with ages 4.7 and 6 Gyr, respectively, are the oldest open clusters with derived Li abundances. Field samples with inhomogeneous ages and kinematics also studied (Pasquini, Liu, & Pallavicini 1994; Favata, Micela, & Sciortino 1996; Chen et al. 2001). For hotter stars, the behavior of A(Li) versus temperature was studied by Lambert, Heath, & Edvardsson (1991) and Boesgaard et al. (2001).

In the present work, we derive Li abundances for a kinematically selected sample. The stars from this sample have highly eccentric orbits, indicating an inner disk or bulge origin. The sample selection and kinematical properties are described in Grenon (1999, 2000). A detailed analysis of these stars was presented in Pompéia, Barbuy, & Grenon (2001, hereafter Paper I). Binaries are rejected using Hipparcos photometry and radial velocity measurements. Isochronal ages are 10–11 Gyr, making this one of the oldest samples with derived Li abundances in the studied metallicity range.

## 2. OBSERVATIONS AND ANALYSIS

The spectra were obtained in 1999 September at the 1.52 m telescope of ESO, La Silla, with the FEROS spectrograph. The standard star+sky configuration was used. The spectral coverage is from 356 to 920 nm, with a R = 48,000 resolution. Data reduction was performed using the ESO pipeline package for reductions of FEROS data in MIDAS environment.

Stellar parameters are those derived in Paper I, where effective temperatures were derived using Hα profiles, and surface gravities were inferred by requiring ionization equilibrium of Fe i and Fe ii lines. MARCS model atmospheres (Gustafsson et al. 1975) were employed. Metallicities and microturbulent velocities were determined by using curves of growth for Fe i and Fe ii. Stellar masses were derived from isochrones of VandenBerg (1985) and VandenBerg & Laskarides (1987). A detailed description of the determination of stellar parameters is presented in Paper I. In Table 1, effective temperatures, gravities, microturbulence velocities, metallicities, and masses are reported.

### Table 1

| Name       | T eff (K) | M/M_☉ (M_☉) | log g (cgs) | [Fe/H] | ξ (km s⁻¹) | A(Li) |
|------------|----------|-------------|-------------|--------|------------|-------|
| HD 143016  | 5755     | 0.85        | 3.8         | -0.50  | 1.0        | <0.8  |
| HD 143102  | 5500     | 1.10        | 3.7         | 0.10   | 0.9        | 1.85  |
| HD 148530  | 5350     | 0.90        | 4.3         | 0.00   | 0.5        | <0.4  |
| HD 149256  | 5350     | 0.80        | 3.6         | 0.26   | 1.1        | <1.0  |
| HD 152391  | 5300     | 0.90        | 3.9         | -0.12  | 0.9        | 1.25  |
| HD 326583  | 5600     | 1.00        | 3.7         | -0.50  | 0.6        | <1.2  |
| HD 175617  | 5550     | 0.80        | 4.7         | -0.48  | 0.5        | <1.4  |
| HD 178737  | 5575     | 0.90        | 4.0         | -0.33  | 0.6        | 1.4   |
| HD 179764  | 5450     | 0.90        | 4.2         | 0.05   | 0.5        | 0.7   |
| HD 181234  | 5350     | 0.90        | 4.1         | 0.38   | 0.8        | <0.5  |
| HD 184846  | 5600     | 0.85        | 4.0         | -0.25  | 0.8        | <0.4  |
| BD-176035  | 4750     | 0.85        | 3.8         | 0.05   | 1.0        | 0.0   |
| HD 198245  | 5650     | 0.80        | 4.3         | -0.65  | 0.5        | <0.6  |
| HD 201237  | 4950     | 0.95        | 4.3         | -0.05  | 0.5        | 0.3   |
| HD 211276  | 5500     | 0.85        | 4.0         | -0.55  | 0.5        | <1.2  |
| HD 211532  | 5350     | 0.80        | 4.7         | -0.70  | 0.5        | <0.8  |
| HD 211706  | 5800     | 1.00        | 3.7         | -0.05  | 1.0        | 2.1   |
| HD 214059  | 5550     | 0.90        | 3.8         | -0.33  | 0.65       | <1.3  |
| CD-401506  | 5350     | 0.90        | 4.1         | -0.10  | 0.5        | 0.5   |
| HD 219180  | 5400     | 0.80        | 4.4         | -0.70  | 0.5        | 1.5   |
| HD 220536  | 5850     | 0.95        | 3.9         | -0.22  | 1.0        | 2.2   |
| HD 220993  | 5600     | 0.90        | 4.0         | -0.30  | 0.7        | <1.4  |
| HD 224383  | 5800     | 1.00        | 4.1         | -0.02  | 1.0        | 1.4   |
| HD 4308    | 5600     | 0.90        | 4.0         | -0.40  | 0.7        | <1.3  |
| HD 6734    | 3000     | 1.05        | 3.1         | -0.53  | 0.8        | <0.8  |
| HD 8638    | 5500     | 0.85        | 4.1         | -0.50  | 0.9        | <0.3  |
| HD 9424    | 5350     | 0.90        | 4.0         | 0.00   | 0.8        | <0.9  |
| HD 10576   | 5850     | 1.00        | 3.6         | -0.12  | 1.25       | 2.3   |
| HD 10785   | 5850     | 0.95        | 4.2         | -0.25  | 1.0        | 1.9   |
| HD 11306   | 5200     | 0.85        | 4.3         | -0.60  | 0.6        | <0.6  |
| HD 11397   | 5400     | 0.80        | 4.0         | -0.70  | 0.6        | <1.5  |
| HD 14282   | 5800     | 0.95        | 3.7         | -0.40  | 1.0        | <1.3  |
| HD 16623   | 5700     | 0.90        | 4.0         | -0.60  | 1.0        | 1.5   |
| BD-02603   | 5300     | 0.90        | 3.9         | -0.75  | 0.8        | <1.5  |
| HD 21543   | 5650     | 0.70        | 4.1         | -0.55  | 0.5        | <1.4  |

### References
-(B) Barbuy et al. 1999, (L) Lambert et al. 1993, (S) Spite & Spite 1982.
2.1. Li Abundances

Li abundances were determined by using synthetic spectra in the region of the Li doublet at \( \lambda 6707.76 \ \text{Å} \). The spectrum synthesis code is described in Cayrel et al. (1991). The atomic line list in the region is reproduced in Table 2, and molecular lines of TiO, C\(_2\), and CN are included.

The \( \lambda 6103.4 \ \text{Å} \) Li line is known to be less perturbed by non-LTE (NLTE) effects than the resonance one at \( \lambda 6707.76 \ \text{Å} \). However, due to the metallicity and atmospheric parameters range of our sample, it is heavily blended and undetectable for most of the stars. The NLTE effects for the \( \lambda 6707.76 \ \text{Å} \) doublet of our sample stars are of the order of \([\text{Li}/\text{H}]/C_{21}\) = 0.012 (Carlsson et al. 1994) and do not affect the results.

Errors in Li abundances are dominated by temperature uncertainties. The estimated error in \( A(\text{Li}) \) is 0.07 dex for a \( T_{\text{eff}} \) change of 100 K. The calculated Li abundances are also reported in Table 1. In Figure 1, the Li line syntheses for HD 211706 and HD 10576 are shown.

3. DISCUSSION

3.1. Li versus \( T_{\text{eff}} \)

In Figure 2, Li abundances versus \( T_{\text{eff}} \) are plotted. Most of the determined abundances for the sample stars represent upper limits, indicating that the line depth is below the limit of 2 \( \sigma \) of the noise. Nevertheless, an upper envelope of high-Li stars is also observed.

A large spread in Li abundances is present for stars with the same temperature. Large spreads in Li abundances were also inferred for other samples of turnoff field stars with different compositions and ages (Lambert et al. 1991; Pasquini et al. 1994; Favata et al. 1996; Chen et al. 2001) and even for very homogeneous samples such as M67 G-type stars (Pasquini et al. 1997; Jones et al. 1999).

3.2. Li versus Age

The correlation between Li abundances and age is examined in Figure 3, where the \( A(\text{Li}) \) versus \( T_{\text{eff}} \) is plotted compared to that for M67. As shown in this figure, the two samples overlap. The lack of a depleted pattern of bulgelike relative to M67 stars suggests that Li depletion mechanisms become inefficient with age. Open cluster observations are in agreement with this suggestion. The depletion rate apparently decreases with time, given that higher depletion is observed among young clusters with different ages (50–600 Myr) than among old clusters (1–4 Gyr; Jeffries 2000). Pasquini (2000) suggested that no depletion mechanism acts for ages older than \( \sim 1.6 \) Gyr. Based on a sample of field stars,
Chen et al. (2001) have also claimed that Li depletion occurs early in life, at ages $\lesssim 1.5$ Gyr. Our sample, with much older stars and with some high-Li, supports this suggestion.

3.3. Li versus Mass

Standard models predict that high-mass stars preserve more of their Li than lower mass stars. In Figure 4, we plotted the $A$(Li) versus mass ($M/M_\odot$). A slight trend of Li abundance with mass is observed, although with some scatter, probably due to the action of other depletion mechanisms such as rotation-driven mechanisms, which depend on the rotation history of the star.

3.4. Li versus $[\text{Fe/H}]$

The depth of the convection zone is larger for higher metallicity stars, therefore these stars are predicted to burn more of their Li than lower metallicity stars with the same temperature. In order to check the role of metallicities in Li depletion, we compare in Figure 5 our Li data to that for NGC 6397 (Castilho et al. 2000), a 11.5 Gyr cluster (Chaboyer 1998) with metallicity $[\text{Fe/H}] = -2.0$. This figure shows that, although older, NGC 6397 stars have preserved more of their Li content than most of the bulgelike stars with the same temperature. On the other hand, some high-Li bulgelike stars are also observed.

In order to test the correlation between metallicity and the Li content, we plotted $A$(Li) versus $[\text{Fe/H}]$ in Figure 6. Different symbols represent different ranges of effective temperature. No apparent trend between Li abundance and metallicity is found for any of the temperature ranges. Nevertheless, a weak correlation with metallicity may be present, contributing to the dispersion in Li abundances.

3.5. Li versus $[\text{O/H}]$

Swenson et al. (1994) developed stellar models taking into account improved interior and surface opacities. They argue that elements such as Si, O, Ne, and Mg may induce opacity changes, resulting in different Li-burning rates. Their results pointed out that oxygen, together with iron, is the main contributor to opacity. They estimated that an oxygen enhancement of $[\text{O/Fe}] \sim +0.20$ could increase significantly the Li depletion rate; using new opacity tables with enhanced oxy-
gen-to-iron ratio, they reproduced the observed pattern of the Hyades stars.

In order to analyze whether or not oxygen abundances contribute to Li depletion, we compared Li abundances with the oxygen abundances derived in Paper I. In Figure 7, $A$(Li) versus $[O/H]$ are plotted. A statistical analysis is performed and a correlation coefficient of $r = -0.23$ is inferred. This coefficient indicates that essentially no dependence exists between Li and oxygen abundances.

4. SUMMARY

In the present work, lithium abundances for a sample of bulgelike stars with isochronal ages of 10–11 Gyr are reported. High-Li and low-Li stars are observed. The overlap between lithium curves for M67, a 4 Gyr open cluster, and our bulgelike sample, ~5 Gyr older, seems to indicate that the depletion mechanisms become inefficient with age, and no depletion occurs during the latter stages (ages older than ~1.5 Gyr) of the MS.

The derived Li abundances show that a high dispersion is present for bulgelike stars with the same temperature comparable to that observed in field samples and in M67 stars. No apparent correlation between $[Fe/H]$ and $A$(Li) is found, although differences in metallicities may account for part of the observed Li dispersion. A spread in the Li abundance versus stellar mass with a possible weak trend is obtained.

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