LITHIUM ABUNDANCES OF EXTREMELY METAL-POOR TURNOFF STARS

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ABSTRACT

We have determined Li abundances for eleven metal-poor turnoff stars, among which eight have [Fe/H] < −3, based on LTE analyses of high-resolution spectra obtained with the High Dispersion Spectrograph on the Subaru Telescope. The Li abundances for four of these eight stars are determined for the first time by this study. Effective temperatures are determined by a profile analysis of Hz and Hα. While seven stars have Li abundances as high as the Spite Plateau value, the remaining four objects with [Fe/H] < −3 have A(Li) = log(Li/H) + 12 ≤ 2.0, confirming the existence of extremely metal-poor (EMP) turnoff stars having low Li abundances, as reported by previous work. The average of the Li abundances for stars with [Fe/H] < −3 is lower by 0.2 dex than that of the stars with higher metallicity. No clear constraint on the metallicity dependence or scatter of the Li abundances is derived from our measurements for the stars with [Fe/H] < −3. Correlations of the Li abundance with effective temperatures, with abundances of Na, Mg, and Sr, and with the kinematical properties are investigated, but no clear correlation is seen in the EMP star sample.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: Population II

1. INTRODUCTION

Over the course of the past few decades, Li abundances have been measured for many metal-poor main-sequence turnoff stars, in hopes of placing constraints on the nature of big bang nucleosynthesis (BBN). The first such investigation, by Spite & Spite (1982), revealed that warm metal-poor main-sequence stars exhibited a constant Li abundance. This so-called Spite Plateau was interpreted as a result of the synthesis of light nuclei in the first several minutes of the evolution of the universe (it is conventionally assumed that Li is not destroyed at the surface of such stars because of their shallow surface convection zones). Since then, measurements of Li abundances have been obtained over wide ranges of effective temperature and metallicity, confirming that the scatter of the Li abundances in most stars with \( T_{\text{eff}} > 5700 \text{ K} \) and \( [\text{Fe/H}] < -1.5 \) is small, if present at all (Ryan et al. 1999, and references therein).10

However, it has been recognized that the Spite Plateau value of \( A(\text{Li}) \sim 2.2 \) is 0.3–0.4 dex lower than the Li abundance predicted by standard BBN models (Coc et al. 2004), adopting the baryon density determined by recent measurements of the cosmic microwave background (CMB) radiation with the WMAP satellite (Spergel et al. 2003). This discrepancy indicates the existence of poorly understood processes that deplete Li in metal-poor turnoff stars (e.g., Korn et al. 2006, 2007), astration of Li in the gas that formed these stars (perhaps by massive zero-metallicity progenitors; Piau et al. 2006), problems in the measured abundances of Li in metal-poor stars, systematic uncertainties in the standard BBN model predictions, or exotic processes in the early universe arising from nonstandard particle physics (Cyburt et al. 2008 and references therein).

Recent measurements of very metal-poor turnoff stars also suggest a decreasing trend of Li abundances with decreasing metallicity (Ryan et al. 1996, 1999; Boesgaard et al. 2005; Asplund et al. 2006). In particular, Bonifacio et al. (2007) investigated the Li abundances for a sample that includes eight stars with \( [\text{Fe/H}] < -3 \). They showed that the Li abundances of these stars are lower than those of stars with higher metallicity, investigating very carefully the scatter and trend of Li abundances with metallicity and effective temperature.

Another unsolved problem is the low Li abundance found in HE 1327–2326, a hyper metal-poor turnoff star having \( [\text{Fe/H}] < -5 \) (Frebel et al. 2005; Aoki et al. 2006). Only an upper limit on the Li abundance has been determined, \( A(\text{Li}) < +0.62 \) (Frebel et al. 2008). Although the star has probably evolved to the subgiant branch (Korn et al. 2009), the effective temperature of this object (6180 K; Frebel et al. 2008) is still sufficiently high that depletion of Li by surface convection is not expected. Another possible explanation for the apparent depletion of Li is mass accretion from an evolved companion star (Ryan et al. 2002), in particular because this star is highly carbon enhanced ([C/Fe] \sim +4.0; Aoki et al. 2006). However, no signature of binarity has been found yet for this object (Frebel et al. 2008).

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3 [A/B] = log(N_A/N_B) \sim log(N_A/N_B)_{0} + log\epsilon_A = log(N_A/N_B) + 12 for elements A and B. Lithium abundances are conventionally presented as A(Li) instead of log \epsilon_{Li}.
Thus, concerning the $^7$Li abundances in very metal-poor stars, we are confronted with three problems: (1) the discrepancy between the observed Spite Plateau value and the prediction of standard BBN models adopting the baryon density determined by CMB measurements, (2) a possible trend of the Li abundance as a function of metallicity in extremely metal-poor (EMP) stars, and (3) the low Li abundance in HE 1327–2326 (see also the summary by Piau et al. 2006). Although possible connections between the above three problems are still unknown, we have obtained measurements of Li abundances for several EMP turnoff stars in a search for hints to solving these Li puzzles.

In this paper, we report measurements of Li abundances for very metal-poor (VMP) and EMP stars. Our sample includes eight stars with $[\text{Fe}/\text{H}] < -3$, among which four stars are studied for the first time. The sample selection and high-resolution spectroscopy are described in Section 2. Section 3 reports the determination of stellar parameters and details of the measurement of Li abundances. Uncertainties and comparisons with previous work are also discussed in this section. We discuss the implications of our measurements in Section 4, and consider possible correlations with the derived stellar atmospheric parameters, other elemental abundances, and the kinematics of the sample.

### 2. OBSERVATIONS

High-resolution spectra of VMP and EMP main-sequence turnoff stars were obtained in the course of three different observing programs, using the Subaru Telescope High Dispersion Spectrograph (HDS; Noguchi et al. 2002). Table 1 lists the objects and details of the observations. The spectra of the first five objects were obtained in an observing program for EMP stars in 2005 (Aoki et al. 2006). The two objects from the SDSS sample were observed in a program for carbon-enhanced metal-poor (CEMP) stars (Aoki et al. 2008). Although these two stars were selected as candidate CEMP turnoff stars having $[\text{Fe}/\text{H}] < -3$, they turned out to show no clear carbon excess in our high-resolution spectroscopy, thus were good targets for studying the Li abundances in the extremely low metallicity range. The other four bright stars were observed with very high signal-to-noise ratios ($S/N$) in order to measure Li isotope ratios (P.I.: S. Inoue).

| Star          | Obs. Date | Exp. | Counts | JD          | $V_H$ (km s$^{-1}$) |
|---------------|-----------|------|--------|-------------|--------------------|
| BS 16545–089  | 2005 Feb 28 | 225  | 16500  | 2453429.86  | $-161.54 \pm 0.09$ |
| CS 22948–093 | 2005 Jun 19 | 174  | 5900   | 2453541.06  | $369.24 \pm 0.30$  |
| CS 22965–054 | 2005 Jun 20 | 100  | 5000   | 2453541.97  | $-281.67 \pm 0.20$ |
| HE 1148–0037 | 2005 Feb 27 | 160  | 15000  | 2453428.94  | $-10.88 \pm 0.16$  |
| CD −24° 17504| 2005 Jun 20 | 20   | 14000  | 2453452.12  | $136.61 \pm 0.13$  |
| SDSS 0040+16d| 2006 Sep 14 | 80   | 4800   | 2453992.90  | $-49.43 \pm 0.07$  |
| SDSS 1033+40d| 2007 Feb 10 | 160  | 4100   | 2454141.98  | $-132.87 \pm 0.27$ |
| G 64–12      | 2003 Feb 22 | 300  | 103000 | 2453507.76  | $434.68 \pm 0.03$  |
| G 64−37      | 2005 May 18 | 420  | 211000 | 2453508.83  | $76.65 \pm 0.06$   |
| HD 84937     | 2003 Feb 22 | 180  | 626000 | 2452692.83  | $-14.63 \pm 0.03$  |
| BD+26 3578† | 2005 May 17 | 132  | 342000 | 2453508.00  | $-91.23 \pm 0.03$  |

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Notes.

a Exposure time (minutes).

b Photon counts per pixel at 6700 Å.

c Heliocentric radial velocity.

d SDSS J004029.17+160416.2 = 0418-51884-574.

e SDSS J103301.41+400103.6 = 1430-53002-498.

† HD 338529.

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Lithium abundances for seven objects in our sample have been recently measured with high-resolution spectroscopy by other authors. The stars CS 22948–093 and CS 22965–054 were studied by Bonifacio et al. (2007). The five bright objects are well-known stars for Li studies. BD+26° 3578 was recently studied by Asplund et al. (2006). Li abundances of G 64−12 and G 64−37 were measured by Ryan et al. (1999) and Boesgaard et al. (2005). Ryan et al. (1999) also determined Li abundances for HD 84937, BD+26° 3578, and CD −24° 17504. Duplications of targets with previous studies provide the opportunity to examine the consistency between independent abundance measurements. The Li abundances of the other four stars (BS 16545–089, HE 1148–0037, SDSS 0040+16, and SDSS 1033+40) are reported for the first time by the present study.

The spectral resolution for the last four stars in Table 1 is $R = 90,000$ or 100,000. The other objects were observed with $R = 60,000$ with 2 × 2 CCD on-chip binning. An exception is SDSS 1033+40, which was observed with $R = 45,000$ to collect sufficient photons, using a wider slit, under relatively poor seeing conditions. The spectra cover 4100–6800 Å, although the coverage is slightly different between the individual observing programs.

Data reduction was carried out with standard procedures using IRAF.11 Photon counts at 6700 Å are listed in Table 1.

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11 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.
Equivalent widths of Fe, Na, Mg, and Sr lines were measured by fitting Gaussian profiles, in order to determine atmospheric parameters and chemical compositions. Since the Li i by fitting Gaussian profiles, in order to determine atmospheric Equivalent widths of Fe, Na, Mg, and Sr lines were measured by calculations of Stehlé & Hutcheon (1999) and Barklem (2007), the role of hydrogen collisions being questionable on the basis of theoretical non-LTE (NLTE) calculations (Barklem 2007), the role of hydrogen collisions being a major uncertainty. Those calculations admit that the temperatures from LTE Balmer line wings could be systematically too cool by of order 100 K if hydrogen collisions are inefficient, although LTE is not ruled out. Due to the fact that there is no strong evidence favoring any particular hydrogen collision model, we chose to calculate in LTE as this temperature scale is well studied, and it is computationally most practical. However, we emphasize that LTE is not a safe middle ground, and will lead to temperatures systematically too cool should departures from LTE exist in reality.

Often, Hα is given higher weight than higher series lines such as Hβ for reasons discussed by Fuhrmann et al. (1993). However, in EMP turnoff stars this is no longer obvious since blending by metal lines becomes unimportant, and Hβ becomes in fact almost insensitive to gravity, while Hα is quite gravity sensitive (see Table 4 of Barklem et al. 2002). Further, the calculations by Barklem (2007) suggest that NLTE effects, if they exist, will be largest in Hα. Thus, in combining the temperatures from Hα and Hβ, we have in fact given Hβ double the weight of Hα.

The derived effective temperatures are dependent on the gravity assumed in the calculation. The analysis is iterated for the gravity, which is determined from the analysis of the high-resolution spectrum (Section 3) for each object. The results and uncertainties of the Teff determinations are listed in Table 2. The uncertainties listed in the tables are estimated from the quality of the spectrum and the fit.

For comparison purposes, we also estimated the effective temperatures from the (V − K)0 colors (Teff(V − K)), using the effective temperature scales of Alonso et al. (1996), Ramírez & Meléndez (2005b), and González Hernández & Bonifacio (2009). For the estimates using the scale of Alonso et al. (1996), we assume [Fe/H] = −3.0 for stars having [Fe/H] < −3.0 following Ryan et al. (1999). The photometry data were collected from Beers et al. (2007), the Two Micron All Sky Survey (2MASS) catalog (Skrutskie et al. 2006), and the

Table 2
Atmospheric Parameters

| Object          | Teff (Hα) (K) | Teff (Hβ) (K) | Teff (Adopted) (K) | σ(Teff) (K) | log g | v micro (km s−1) | A(Fe)/Fei | A(Fe)/Feii |
|-----------------|---------------|---------------|---------------------|-------------|------|------------------|-----------|-----------|
| BS 16545-089    | 6380          | 6290          | 6320                | 150         | 3.9  | 1.5              | 3.96      | 3.88      |
| CS 22948-093    | 6320          | 6410          | 6380                | 150         | 4.4  | 1.5a             | 4.02      | 4.02      |
| CS 22965-054    | 6390          | 6270          | 6310                | 200         | 3.9  | 1.5a             | 4.61      | 4.56      |
| HE 1148-0037    | 6100          | 5940          | 5990                | 200         | 3.7  | 1.5              | 3.99      | 3.90      |
| CD −24°17504    | 6150          | 6190          | 6180                | 150         | 4.4  | 1.5              | 4.05      | 4.17      |
| SDSS 0040+16    | 6350          | 6360          | 6360                | 200         | 4.4  | 1.5a             | 4.16      | 4.25      |
| SDSS 1033+40    | 6380          | 6370          | 6370                | 200         | 4.4  | 1.5a             | 4.22      | 4.29      |
| G 46−12         | 6260          | 6280          | 6270                | 100         | 4.4  | 1.5              | 4.08      | 4.20      |
| G 64−37         | 6310          | 6280          | 6290                | 100         | 4.4  | 1.5              | 4.23      | 4.33      |
| HD 84937        | 6330          | 6270          | 6290                | 100         | 3.9  | 1.2              | 5.30      | 5.35      |
| BD+26°3578      | 6370          | 6330          | 6340                | 100         | 3.9  | 1.5              | 5.17      | 5.20      |

**Table 2 Note.** *Assumed values (see the text).*

### 3. STELLAR PARAMETERS AND LI ABUNDANCE MEASUREMENTS

#### 3.1. Effective Temperatures

The effective temperatures (Teff’s) of our program stars were determined from profile fits to hydrogen Balmer lines, a technique used as well by Asplund et al. (2006) and Bonifacio et al. (2007). We employed the Hα and Hβ lines (Teff(Hα) and Teff(Hβ)). Although Hγ is also covered by our observations, it lies at the edge of the CCD, making continuum rectification difficult, and thus has not been used. The method for continuum rectification of the observed spectra and analysis used follows exactly that described in Barklem et al. (2002), which may be consulted for details. The most important aspects of the analysis are that the synthetic profiles are computed assuming LTE line formation using one-dimensional LTE plane-parallel MARCS models (Asplund et al. 1997), with convection described by mixing length theory with parameters α = 0.5 and γ = 0.5. The most important line-broadening mechanisms for the wings are Stark broadening and self-broadening, which are described by calculations of Stehlé & Hutcheon (1999) and Barklem et al. (2000), respectively. The fitting is accomplished by minimization of the χ² statistic, comparing the observed and synthetic profiles. Essentially the same method was used by Asplund et al. (2006), although with some differences in the rectification and profile comparison techniques.

We note that the assumption of LTE for formation of the Balmer line wings in cool stars has recently been shown to be questionable on the basis of theoretical non-LTE (NLTE) calculations (Barklem 2007), the role of hydrogen collisions being a major uncertainty. Those calculations admit that the temperatures from LTE Balmer line wings could be systematically too cool by of order 100 K if hydrogen collisions are inefficient, although LTE is not ruled out. Due to the fact that there is no strong evidence favoring any particular hydrogen collision model, we chose to calculate in LTE as this temperature scale is well studied, and it is computationally most practical. However, we emphasize that LTE is not a safe middle ground, and will lead to temperatures systematically too cool should departures from LTE exist in reality.

Often, Hα is given higher weight than higher series lines such as Hβ for reasons discussed by Fuhrmann et al. (1993). However, in EMP turnoff stars this is no longer obvious since blending by metal lines becomes unimportant, and Hβ becomes in fact almost insensitive to gravity, while Hα is quite gravity sensitive (see Table 4 of Barklem et al. 2002). Further, the calculations by Barklem (2007) suggest that NLTE effects, if they exist, will be largest in Hα. Thus, in combining the temperatures from Hα and Hβ, we have in fact given Hβ double the weight of Hα.

The derived effective temperatures are dependent on the gravity assumed in the calculation. The analysis is iterated for the gravity, which is determined from the analysis of the high-resolution spectrum (Section 3) for each object. The results and uncertainties of the Teff determinations are listed in Table 2. The uncertainties listed in the tables are estimated from the quality of the spectrum and the fit.

For comparison purposes, we also estimated the effective temperatures from the (V − K)0 colors (Teff(V − K)), using the effective temperature scales of Alonso et al. (1996), Ramírez & Meléndez (2005b), and González Hernández & Bonifacio (2009). For the estimates using the scale of Alonso et al. (1996), we assume [Fe/H] = −3.0 for stars having [Fe/H] < −3.0 following Ryan et al. (1999). The photometry data were collected from Beers et al. (2007), the Two Micron All Sky Survey (2MASS) catalog (Skrutskie et al. 2006), and the
SIMBAD database. The $V$ magnitudes of the SDSS stars are derived from the $g$ magnitude and $g - r$ color, as in Aoki et al. (2008). Interstellar reddening is estimated from the dust maps of Schlegel et al. (1998) and from the interstellar Na D line, using the scale of Munari & Zwitter (1997); results are listed in Table 3. We adopt the reddening estimate obtained from the Na D line for the brightest four stars (HD 84937, BD+26°3578, G 64−12, and G 64−37) because these are nearby stars, and the reddening might be overestimated from the dust maps. The interstellar Na D lines blend with the stellar lines in the spectrum of HE 1148−0037, so the reddening value from the dust map is adopted. The differences between the reddening values derived from the two methods are adopted.

The photometry data and the derived effective temperatures are listed in Table 3. Figure 2 shows the differences between the effective temperatures from Balmer lines and those from $V − K$ colors for the three temperature scales. The effective temperatures from the scales of Ramírez & Meléndez (2005b) and González Hernández & Bonifacio (2009) are systematically higher than those from Alonso et al. (1996). The differences between the results from González Hernández & Bonifacio (2009) and from Alonso et al. (1996) are 100−150 K. The effective temperatures adopted in the analysis. We discuss the impact of effective temperatures on the metallicity dependence of Li abundances in Section 4.

The estimate of effective temperatures for EMP stars from these temperature scales would be rather uncertain, because of the small number of stars in the sample used to produce the scales. Alonso et al. (1996) includes a very small number of stars for the ranges of the color and metallicity. Ramírez & Meléndez (2005a) increased the number of such stars, which are used to produce the scale of Ramírez & Meléndez (2005b). However, the sample is still not large (10 stars) and includes one carbon-enhanced star and two known double-lined spectroscopic binaries. Further measurements of effective temperatures by the infrared flux method are desired for this metallicity range.
The abundance analyses were made using the grid of ATLAS9 NEWODF model atmospheres (Kurucz 1993; Castelli & Kurucz 2003), with enhancement of the $\alpha$ elements. Calculations of synthetic spectra for abundance analyses were made employing a one-dimensional LTE spectral synthesis code that is based on the same assumptions as the model atmosphere program of Tsuji (1978). The surface gravities (log $g$) are estimated from the effective temperatures and $Y$ isochrones (Kim et al. 2002) for [Fe/H] = −2.5 (for HD 84937 and BD+26°3578) and [Fe/H] = −3.5 (for the others) assuming the ages of these stars to be 12 Gyr. For the $T_{\text{eff}}$ range of our sample, two possibilities of log $g$ exist: the subgiant case (log $g$ ∼ 3.8) and the main-sequence case (log $g$ ∼ 4.4). We performed abundance analyses for Fe i and Fe ii (see below for details), and selected the log $g$ that provides better agreement of iron abundances from the two species for each star. The derived log $g$ value is not sensitive to the assumption of the age for selecting isochrones. The results for log $g$ and the derived iron abundances from the two species are listed in Table 2. We determined effective temperature when the gravity assumed in the first estimate of effective temperature is different from the derived one. We note that the Fe abundance from Fe i lines and the Li abundance are not sensitive to the gravity adopted in the analysis.

The analysis, when adopting the microturbulent velocity ($v_{\text{micro}}$) of 1.5 km s$^{-1}$, results in no statistically significant dependence of the iron abundances on the strengths of the Fe i lines used for the analysis for BS 16545−089, HE 1148−0037, G 64−12, G 64−37, and BD+26°3578, while 1.2 km s$^{-1}$ is preferable for HD 84937. Since the number of iron lines available in the abundance analyses of the other four stars is too small to estimate their microturbulent velocity, we assume $v_{\text{micro}}$ of 1.5 km s$^{-1}$ for these objects. We note that the Li abundance derived from the weak Li i 6708 Å line is insensitive to the microturbulent velocity adopted in the analysis.

In the following discussion, we adopt the iron abundances from Fe i lines (Table 2) as the metallicity. Although the iron abundances from Fe i lines are considered to be possibly affected by NLTE effects (Asplund 2005, and references therein), our results are insensitive to the gravity adopted in the analysis. We refer to a solar Fe abundance of log $e_{\odot}$(Fe) = 7.45 (Asplund et al. 2005) to derive the [Fe/H] and [X/Fe] values.

In order to investigate correlations between the abundances of Li and other elements, Na, Mg, and Sr abundances are determined by a standard LTE analysis from the Na i 5890 and 5896 Å lines (D lines), Mg i 5172, 5183, and/or 5528 Å lines, and Sr ii 4078 and/or 4215 Å lines, respectively. The agreement of the abundances from two or three lines for each element is fairly good. The results are listed in Table 4. Correlations between the abundances of Li and these elements are examined in Section 4. The Na D lines are known to suffer a significant NLTE effect that is dependent on the line strengths. The effect is, however, not large ($\Delta$[Na/Fe]$_{\text{NLTE}}$ − [Na/Fe]$_{\text{LTE}}$ ≲ 0.1 dex) for the EMP stars that have equivalent widths of the D lines less than 50 mA (Takeda et al. 2003; Andrievsky et al. 2007). The effect could be larger (∼−0.3 dex) for the less metal-poor stars whose equivalent widths are as large as 100 mA.

### Table 4

| Object         | [Fe/H] | W (mÅ) | $\Delta$(Li) | $\sigma$(Fe[$\text{Li}$]) | $\sigma$(Fe[$\text{Li}$]) | [Na/Fe] | [Mg/Fe] | [Sr/Fe] |
|----------------|--------|--------|--------------|--------------------------|--------------------------|---------|---------|---------|
| BS 16545−089   | −3.49  | 15.3   | 2.02         | 0.12                     | 0.17                     | −0.12   | 0.25    | −0.34   |
| CS 22948−093   | −3.43  | 14.2   | 1.96         | 0.12                     | 0.17                     | −0.22   | 0.13    | 0.13    |
| CS 22965−054   | −2.84  | 20.3   | 2.16         | 0.12                     | 0.19                     | 0.05    | 0.26    | 0.45    |
| HE 1148−0037   | −3.46  | 19.3   | 1.90         | 0.08                     | 0.17                     | 0.14    | 0.25    | −0.64   |
| CD −24°17504   | −3.40  | 21.2   | 2.08         | 0.06                     | 0.13                     | −0.13   | 0.31    | <−0.9   |
| SDSS 0040+16   | −3.29  | 13.6   | 1.99         | 0.14                     | 0.20                     | 0.19    | 0.32    | −0.39   |
| SDSS 1033+40   | −3.24  | 16.5   | 2.09         | 0.18                     | 0.23                     | −0.24   | 0.03    | −0.32   |
| G 64−12        | −3.37  | 22.4   | 2.18         | 0.02                     | 0.07                     | −0.06   | 0.37    | 0.08    |
| G 64−37        | −3.23  | 16.2   | 2.04         | 0.02                     | 0.07                     | −0.14   | 0.24    | 0.01    |
| HD 84937       | −2.15  | 24.7   | 2.26         | 0.02                     | 0.07                     | 0.28    | 0.28    | 0.22    |
| BD+26°3578     | −2.28  | 23.7   | 2.28         | 0.02                     | 0.07                     | 0.22    | 0.35    | 0.04    |

#### 3.2. Other Parameters and Abundances

The Li abundances are derived from the Li i 6708 Å line by fitting the observed spectra with synthetic spectra. Doppler corrections for the observed spectra are determined by the Fe i line positions used for the above abundance measurements. In the fitting procedure for the four bright stars (HD 84937, BD+26°3578, G 64−12, and G 64−37), a small wavelength shift is included as a fitting parameter (see below). The continuum level is estimated from the wavelength range around the Li line (6706.9−6707.4 Å and 6708.2−6708.7 Å). The list of the Li lines provided by Smith et al. (1998) is adopted, neglecting the contribution of 6Li. We assume a Gaussian profile to account for the broadening by macroturbulence, including rotation, and by the instrument. We assume a broadening of 7 km s$^{-1}$ for the stars observed with $R$ ≳ 90,000, and 8 km s$^{-1}$ for the others, values that sufficiently explain the widths of weak Fe lines. We performed the analyses changing the value by ±1 km s$^{-1}$, and confirmed that the effect of the assumed line broadening on the derived Li abundance is small (∼0.01 dex).

We then search for the Li abundance that yields the minimum $\chi^2$. We found that the fit is slightly improved by allowing a small wavelength shift for the four brightest stars, while the effect is negligible for the others. Hence, in our procedure for fitting of the synthetic spectra to the observations, the free parameter was the Li abundance, and for the four brightest stars also a wavelength shift. The number of data points to which the fitting is applied is 18 and 36 for the cases of two pixel binning and of no binning, respectively. The $2\sigma$ range is adopted as the fitting error ($\sigma$[Fe[Li]$]_{\text{fit}}$ in Table 4). While the fitting errors for the four bright stars (G 64−12, G 64−37, HD 84937, and BD+26°3578) are on the order of 0.02 dex and are smaller than the other errors (see below), those for the other fainter stars are 0.06−0.18 dex, depending on the S/N of the spectra.

The equivalent widths of the Li doublet are determined by integrating the flux density of the synthetic spectra calculated for the final Li abundance as mentioned in Section 2. The values are listed in Table 4.
3.4. Uncertainties

In addition to the above fitting errors, the uncertainties in the adopted continuum levels, macroturbulence, and atmospheric parameters should be considered. The continuum level is estimated for the wavelength range around the Li doublet, in which 25 (in the case of two pixel binning) or 50 (in the case of no binning) data points exist. The uncertainty is 0.1% or smaller for the four bright stars (S/N > 300), while it is approximately 0.5% for the spectra with S/N ~ 50. The effects of continuum level shifts of 0.1% and 0.5% are estimated to be 0.01 dex and 0.04 dex, respectively, by means of an analysis of the spectrum region near the Li doublet. The errors due to the uncertainty of the macroturbulent velocity are on the order of 0.01 km s\(^{-1}\), as mentioned above.

The errors due to the uncertainties in atmospheric parameters are estimated by changing the parameters by \(\delta(T_{\text{eff}}) = +100 \text{ K}\), \(\delta(\log g) = -0.3 \text{ dex}\), and \(\delta(v_{\text{micro}}) = +0.3 \text{ km s}^{-1}\) for G 64–12. The effect of metallicity changes of 0.2 dex on the abundance analyses is negligible for EMP stars. We confirmed that the effects of changes of log \(g\) and \(v_{\text{micro}}\) on the derived Li abundance are negligible. The Li abundance changes by \(+0.07 \text{ dex}\) when \(T_{\text{eff}}\) is changed by \(+100 \text{ K}\). Such error estimates are scaled for the uncertainty for \(T_{\text{eff}}\) for each object listed in Table 2.

The total abundance errors \((\sigma[A\text{(Li)}]_{\text{tot}})\) are obtained by adding, in quadrature, the fitting errors and the errors due to the uncertainty of the continuum placement, the macroturbulence, and the effective temperature for each star (see Table 4).

3.5. Comparisons with Previous Work

Table 5 compares the results of the present study for stars in common with other recent studies. The \(T_{\text{eff}}\) and \(A\text{(Li)}\) of CS 22948–093 determined by this work and by Bonifacio et al. (2007) agree fairly well, while a significant discrepancy of \(A\text{(Li)}\) is found for CS 22965–054. This is clearly caused by the different effective temperatures adopted in the two analyses. The uncertainties of \(T_{\text{eff}}\) and \(A\text{(Li)}\) from this grid is systematically higher by 0.06 dex than that obtained from the no overshooting models by conducting analysis with both models. The discrepancy of \(A\text{(Li)}\) derived by us and Boesgaard et al. (2005) is explained by the differences of \(T_{\text{eff}}\) and the model atmosphere grid. The \(T_{\text{eff}}\) of Boesgaard et al. (2005) is spectroscopically determined by the analysis of Fe\text{II} lines. A systematic difference between \(T_{\text{eff}}\)'s from the excitation equilibrium and those from other methods (such as photometric colors) have been reported by previous studies (e.g., Norris et al. 2001; Barklem et al. 2005), which might be attributed to NLTE effects on Fe line formation, although the recent work by Hosford et al. (2009) reported no discrepancy between the \(T_{\text{eff}}\) from LTE analyses of Fe\text{II} lines and \(T_{\text{eff}}\) from the He\text{I} profile analysis.

The \(T_{\text{eff}}\)’s determined by Ryan et al. (1999) are systematically lower than ours. The differences in \(T_{\text{eff}}\) for G 64–12, G 64–37, and CD–24'17504 are smaller than 100 K, while the discrepancies are as large as 200 K for HD 84937 and BD+26'3578. The discrepancy of \(A\text{(Li)}\)’s between the two studies is basically explained by the differences in the adopted effective temperatures.

The above comparisons demonstrate that the differences of derived Li abundances are due to differences of the effective temperature and/or the model atmosphere grid adopted in the analysis. These effects are systematic, and do not essentially affect the discussion of the slope or scatter of Li abundances if the same technique of effective temperature estimates and similar model atmosphere grids are used.

4. DISCUSSION

4.1. Low Li Abundances for Extremely Metal-Poor Stars

Figure 3 shows the Li abundances as a function of [Fe/H] for our sample and others.\(^{12}\) We confirm that the Li abundance of the “reference” star BD+26'3578 ([Fe/H] ~ −2.3) determined by our analysis agrees well with the measurement by Asplund et al. (2006). By contrast, stars with [Fe/H] < −3 (the EMP stars) appear to have lower Li abundances on average, and also exhibit some scatter. We discuss this point further below.

The average of \(A\text{(Li)}\) (i.e., \(\langle A\text{(Li)} \rangle\)) of the eight stars with [Fe/H] < −3 is 2.03, with a sample standard deviation \((\sigma)\) of 0.09 dex. The standard deviation is comparable with, or slightly

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### Table 5
Comparison with Previous Work

| Object         | This Work  | Previous Work (1) | Previous Work (2) |
|----------------|------------|-------------------|-------------------|
|                | \(T_{\text{eff}}\) (K) | \(A\text{(Li)}\)  | \(T_{\text{eff}}\) (K) | \(A\text{(Li)}\)  | Ref.     | \(T_{\text{eff}}\) (K) | \(A\text{(Li)}\)  | Ref.     |
| CS 22948–093   | 6380       | 1.96              | 6356              | 1.94              | Bonifacio et al. (2007) |
| CS 22965–054   | 6310       | 2.16              | 6089              | 2.03              | Bonifacio et al. (2007) |
| BD+26'3578     | 6340       | 2.28              | 6335              | 2.25              | Asplund et al. (2006) |
| G 64–12        | 6270       | 2.18              | 6074              | 2.15              | Boesgaard et al. (2005) |
| G 64–37        | 6290       | 2.04              | 6122              | 1.97              | Boesgaard et al. (2005) |
| CD–24'17504    | 6180       | 2.08              |                   |                   |                     |
| HD 84937       | 6290       | 2.26              |                   |                   |                     |

\(^{12}\) In the figure, the [Fe/H] values of Bonifacio et al. (2007) and Asplund et al. (2006) are adopted without any correction. The solar Fe abundance adopted by Bonifacio et al. (2007) is 7.51, while that of Asplund et al. (2006) is determined by their own analysis of the solar spectrum. Asplund et al. (2006) also reported Fe abundances from Fe\text{II} lines, which are systematically higher by 0.08 dex than those from Fe\text{II} lines according to the authors. Hence, a possible shift of [Fe/H] values by at most 0.1 dex should be taken into consideration in the comparisons of the three works.
smaller than, the measurement errors of our analysis (0.07–0.23 dex). Hence, we do not detect any significant scatter of the Li abundances in our sample of EMP stars. The \( \langle A(\text{Li}) \rangle \) is lower by 0.24 dex and 0.20 dex than the average of our two reference stars (2.27) and the average of the results of the LTE analysis by Asplund et al. (2006) for six stars in reference stars (2.27) and the average of the results of the LTE lower by 0.24 dex and 0.20 dex than the average of our two respectively. Large open circles are overplotted for subgiant stars (log \( g \) < 4.0).

"The effective temperatures derived using the scale of González Hernández & Bonifacio (2009) are adopted, the values are 290 K and 150 K smaller than, the measurement errors of our analysis (0.07–0.23 dex). Hence, we do not detect any significant scatter of the Li abundances in our sample of EMP stars. The \( \langle A(\text{Li}) \rangle \) is lower by 0.24 dex and 0.20 dex than the average of our two reference stars (2.27) and the average of the results of the LTE analysis by Asplund et al. (2006) for six stars in \( -2.5 < [\text{Fe/H}] < -2.0 \) (2.23), respectively. The difference of 0.2 dex is significant, compared to the \( \sigma N^{-1/2} = 0.09/\sqrt{N} = 0.03 \) dex, where \( N \) is the number of objects in the EMP sample. We note that the Li abundances for stars in \( -2.5 < [\text{Fe/H}] < -2.0 \) are well determined by Asplund et al. (2006), and the scatter is small (\( \sigma = 0.04 \) dex and \( \sigma N^{-1/2} = 0.02 \) dex). We conclude that the Li abundances for stars with \( [\text{Fe/H}] < -3 \) are 0.2 dex lower than those of stars with higher metallicity on average, while no significant scatter or trend with metallicity is detected in our EMP sample. A similar conclusion was reached by Bonifacio et al. (2007); our new measurements for stars in the lowest metallicity range support their results.

Such a difference can obviously be produced by a decreasing trend (slope) of \( A(\text{Li}) \) as a function of metallicity. The possible slope of \( A(\text{Li}) \) was discussed by Bonifacio et al. (2007) in detail. However, no clear physical reason for the slope, which appears only at the lowest metallicity range, has yet been identified. Another possibility is that scatter of \( A(\text{Li}) \) increases in the range \( [\text{Fe/H}] < -3 \), and, as a result, the average decreases. This case would be relatively easily explained by depletion of Li, although some reason for the metallicity dependence of the depletion is also required.

If the effective temperatures estimated from the \((V-K)_{0}\) colors using the scales of Ramírez & Meléndez (2005b) and González Hernández & Bonifacio (2009) are employed, the Li abundances of our stars would be systematically higher. The effective temperatures derived using the scale of González Hernández & Bonifacio (2009) are systematically higher by 220 K and 150 K than the values from the Balmer line analysis for EMP stars and for stars with \( [\text{Fe/H}] \approx -2.3 \), respectively, resulting in 0.15 dex and 0.10 dex higher Li abundances. Although the difference of Li abundances between the EMP stars and less metal-poor stars becomes slightly smaller than the result derived adopting the effective temperature from the Balmer line analysis, the difference is still significant. By contrast, if the effective temperatures estimated using the scales of Ramírez & Meléndez (2005b) are adopted, the values are 290 K and 150 K higher than those from the Balmer lines, resulting in 0.20 dex and 0.10 dex higher Li abundances. In this case, the difference of Li abundances between the stars with \( [\text{Fe/H}] < -3 \) and \( > -2.5 \) is only 0.1 dex, which is no longer significant compared to our measurement errors.

4.2. Correlations with Stellar Parameters, Elemental Abundances, and Kinematics

Although no statistically significant scatter of \( A(\text{Li}) \) is found for our full EMP sample, within our measurement errors, the existence of some star-to-star differences in \( A(\text{Li}) \) is suggested.
For instance, even if the stars with the largest measurement errors are excluded from the evaluation, a similar scatter of \( A(Li) \) remains. A difference of 0.14 dex is found in \( A(Li) \) for the two bright stars G 64–12 and G 64–37, as found by Boesgaard et al. (2005) and Nissen et al. (2005). In this subsection, we investigate correlations between \( A(Li) \) and the adopted stellar parameters, in order to search for a hint for understanding the lower Li abundances among the EMP stars.

Figure 4 shows \( A(Li) \) as a function of \( T_{\text{eff}} \). No clear correlation can be seen in this figure. It should be noted that the random error of the effective temperature propagates into the derived Li abundance, which is represented by the arrows shown in the diagram. An increasing trend of Li abundance with decreasing \( T_{\text{eff}} \) is potentially influenced by this error.

Our sample includes stars that have already evolved to the subgiant branch. Their effective temperatures during the main-sequence stage should be higher than the current values, and might be as high as the hottest stars among the main-sequence sample. The stars having \( \log g < 4.0 \) are overplotted by large circles representing candidate subgiants in the figure. If these stars are excluded, we find that stars cooler than 6150 K exhibit higher and almost constant Li abundances, while the warmer stars show some scatter. However, this probably reflects a metallicity effect, as the cooler stars (excluding subgiants) are objects having \( [\text{Fe}/\text{H}] > -2 \) studied by Asplund et al. (2006), while the warmer stars have \( [\text{Fe}/\text{H}] < -2 \). That is, the sample of very metal-poor stars \(( [\text{Fe}/\text{H}] < -2 )\) have \( T_{\text{eff}} > 6150 \) K, or are subgiants. This could be due to a bias in the sample selection caused by the fact that distant stars must be observed to cover lower metallicity ranges, and intrinsically faint stars are not sampled. Other than this point, no clear correlation appears between the Li abundances and effective temperature, even if subgiants are removed from the plot, or if the highest temperature among the sample \(( \approx 6500 \) K) is assigned for them as their \( T_{\text{eff}} \) during their main-sequence phase.

Figure 5 shows Li abundances as functions of \([\text{Na}/\text{Fe}], [\text{Mg}/\text{Fe}], \) and \([\text{Sr}/\text{Fe}]\). An anticorrelation between the Li abundance and the \([\text{Na}/\text{Fe}] \) ratio was reported for the globular cluster NGC 6752 by Pasquini et al. (2005). Such a trend is, however, not seen in our sample (Figure 5): the two low Li stars HE 1148–0037 and SDSS 0040+16 have comparatively high \([\text{Na}/\text{Fe}] \) ratios, while that of the other low Li star, CS 22948–093, is low. If the NLTE effects on the Na abundances are taken into consideration, the abundances of less metal-poor stars become lower by about 0.3 dex. However, this correction does not result in any correlation between the Li and Na abundances.

No significant scatter is found for \([\text{Mg}/\text{Fe}] \) in our sample. Also, no correlation is found between the abundances of Li and the Mg abundances. In contrast, a large scatter of measured Sr abundances exists, which could reflect the contribution of a neutron-capture process that is efficient in the very early Galaxy (Truran et al. 2002; Travaglio et al. 2004; Aoki et al. 2005), as well as the contribution of the main r-process to higher metallicity objects. No correlation is found between the Li and Sr abundances, indicating that the Li production or depletion is not likely to be related to neutron-capture nucleosynthesis processes.

We are also interested in exploring whether the kinematics of the stars with lower \( A(Li) \) exhibit any peculiarities that distinguish them from the rest of the stars. For this exercise,
we combined our present sample with that of Bonifacio et al. (2007). Proper motions of SDSS stars are listed in the public DR6 database, while those of other stars are taken from the NOMAD database (Zacharias et al. 2004). Distances were estimated from the luminosity classifications given by either the present paper or in Bonifacio et al. (2007), applying the methods described by Beers et al. (2000). Stars with log $g > 4.0$ were considered dwarfs, those with $3.5 \leq \log g \leq 4.0$ were considered main-sequence turnoff stars, and those with $\log g < 3.5$ were considered subgiants. The adopted surface gravities, metallicities, photometry, distances, radial velocities, and proper motions are listed in Table 6. These data were used to derive the full space motions and other orbital information, following the procedures described by Carollo et al. (2007); results are listed in Table 7.

Figure 6 shows the derived rotational velocity with respect to the Galactic center, $V_\phi$, as a function of [Fe/H]. The stars with low values of $A$(Li) are labeled by filled circles. We note that three stars with “normal” $A$(Li) are on highly prograde orbits (an additional star, CS 31061–0032, with $V_\phi = 205$ km s$^{-1}$, may be a member of the metal-weak thick disk). This is somewhat unexpected, given the essentially zero net rotation of the inner halo, and net retrograde rotation of the outer halo. We plan to study these stars in more detail in the near future.

Based on the derived space velocities and orbital parameters, an attempt was made to assign approximate population memberships for these stars, listed in the second column of Table 7. The assignments take into account the values of the velocity ellipsoids derived for the inner and outer halo, and the thick disk (including the metal-weak thick disk; D. Carollo et al. 2009, in preparation), as well as the derived $Z_{max}$ (the maximum distance from the Galactic plane in the vertical direction) for each star. We did not attempt to assign a membership to the four highly prograde stars, because, as was mentioned above, they require further investigation (FI in the second column of Table 7). Note that in some cases it was not possible to uniquely

### Table 7

| Star Name | Pop$^a$ | $A$(Li) | $U$ (km s$^{-1}$) | $V$ (km s$^{-1}$) | $W$ (km s$^{-1}$) | $V_\phi$ (km s$^{-1}$) | $v_\text{max}$ (kpc) | $v_\text{min}$ (kpc) | $Z_{max}$ (kpc) |
|-----------|--------|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| BS 16023–0046 | IH | 2.18 | 9 | −237 | 30 | −17 | 0.901 | 8.3 | 0.4 | 1.1 |
| BS 16968–0061 | IH | 2.17 | 51 | −165 | −44 | 54 | 0.722 | 8.3 | 1.3 | 1.1 |
| BS 17570–0063 | IH/OH | 2.05 | 60 | −322 | −45 | −108 | 0.499 | 9.3 | 3.1 | 1.3 |
| CS 21777–0009 | IH/OH | 2.20 | −298 | −80 | 147 | 126 | 0.840 | 32.8 | 2.8 | 13.9 |
| CS 22888–0031 | IH/OH | 2.03 | 196 | −153 | 50 | 65 | 0.788 | 12.5 | 1.4 | 2.8 |
| CS 22948–0093 | IH/OH | 1.92 | −329 | −120 | −201 | 99 | 0.854 | 38.3 | 3.0 | 30.9 |
| CS 22953–0037 | FI | 2.16 | 191 | 109 | 89 | 338 | 0.677 | 37.2 | 7.1 | 8.0 |
| CS 22965–0054 | IH | 2.06 | 250 | −189 | 90 | 0 | 0.999 | 16.3 | 0.0 | 7.5 |
| CS 22966–0011 | IH | 1.91 | −19 | −164 | 7 | 55 | 0.716 | 8.3 | 1.3 | 0.8 |
| CS 29499–0060 | FI | 2.16 | 82 | 51 | 53 | 270 | 0.346 | 15.7 | 7.6 | 2.3 |
| CS 29506–0007 | IH | 2.15 | −106 | −126 | −56 | 98 | 0.557 | 8.8 | 2.5 | 1.8 |
| CS 29506–0090 | IH | 2.10 | −90 | −172 | 24 | 51 | 0.758 | 8.6 | 1.1 | 0.8 |
| CS 29518–0020 | TD/IH | 2.13 | 43 | −68 | 38 | 152 | 0.304 | 8.8 | 4.7 | 1.2 |
| CS 29518–0043 | IH | 2.14 | 85 | −105 | −121 | 116 | 0.453 | 10.3 | 3.8 | 4.6 |
| CS 29527–0015 | IH | 2.08 | 150 | −209 | −81 | 7 | 0.970 | 11.3 | 0.1 | 2.9 |
| CS 30301–0024 | TD/IH | 2.10 | 60 | −108 | −23 | 111 | 0.493 | 8.4 | 2.8 | 0.6 |
| CS 30339–0069 | IH | 2.13 | 68 | −176 | −22 | 44 | 0.774 | 8.8 | 1.1 | 1.6 |
| CS 31061–0032 | TD | 2.22 | −19 | −15 | −33 | 205 | 0.073 | 9.1 | 7.9 | 0.9 |
| CS 16545–0089 | IH | 2.02 | −192 | −87 | −95 | 132 | 0.655 | 16.3 | 3.4 | 4.4 |
| CS 22948–0093 | OH | 1.96 | −332 | −120 | −205 | 99 | 0.857 | 39.8 | 3.0 | 32.4 |
| CS 22965–0054 | IH/OH | 2.16 | 250 | −190 | 90 | 0 | 1.000 | 16.3 | 0.0 | 7.5 |
| HE 1148–0037 | IH | 1.90 | 71 | −185 | −124 | 39 | 0.727 | 9.29 | 1.47 | 5.8 |
| CD −24°17504 | OH | 2.08 | 135 | −388 | −294 | −169 | 0.607 | 28.9 | 7.0 | 23.7 |
| SDSS 0040+16 | IH | 1.99 | 91 | −269 | −110 | −59 | 0.688 | 10.6 | 1.9 | 5.0 |
| SDSS 1033+40 | FI | 2.09 | −86 | 127 | −101 | 347 | 0.602 | 37.1 | 9.2 | 9.8 |
| G 64−12 | OH | 2.18 | −48 | −308 | 391 | −89 | 0.657 | 40.2 | 8.3 | 39.0 |
| G 64−37 | IH/OH | 2.04 | −183 | −332 | −131 | −113 | 0.642 | 14.3 | 3.1 | 6.1 |
| HD 84937 | IH | 2.26 | −214 | −203 | 0 | 15 | 0.955 | 13.5 | 0.3 | 0.0 |
| BD+26°3578 | TD/IH | 2.28 | −51 | −112 | −52 | 108 | 0.497 | 8.7 | 2.9 | 0.9 |

Note. $^a$Assigned stellar population—TD: thick disk (including metal-weak thick disk); IH: inner halo; OH: outer halo; FI: further inspection required.

Figure 6. $V_\phi$ as a function of [Fe/H] for our sample and that of Bonifacio et al. (2007). The filled circles indicate stars with $A$(Li) < 2.0, while the open ones indicate stars with $A$(Li) > 2.0. A typical error of Fe abundance determination is 0.15 dex. Note the presence of several stars with rather high $V_\phi$. 

distinguish a single population assignment, so multiple assignments are given.

Inspection of these assignments indicates no tendency for the stars with low $A$(Li) to be associated preferentially with either the inner- or outer-halo populations. This is similar to the conclusions drawn by Bonifacio et al. (2007) based on inspection of radial velocities alone. However, the sample size (especially of low $A$(Li) stars) and the existing errors on the Li abundance determinations preclude a final determination.

4.3. Summary and Concluding Remarks

Our measurements of the Li doublet for EMP stars based on the effective temperatures from the Balmer lines showed that the Li abundances in the metallicity range [Fe/H] < −3 are lower, on average, than for stars with higher metallicity. The same conclusion is reached by adopting the effective temperatures from $(V - K)_{0}$ using the scales of Alonso et al. (1996) and González Hernández & Bonifacio (2009), although the Li abundances are systematically higher if the latter is adopted. If the temperature scale of Ramírez & Meléndez (2005a) for $(V - K)_{0}$ is adopted, the dependence of the Li abundances on metallicity becomes marginal.

Although no scatter or trend of Li abundances is detected within the sample of EMP stars, the metallicity dependence of the Li abundance could be a key to understanding the Li problems found for metal-poor stars. Observations to obtain better quality spectra for such EMP stars, to improve measurements of the Li feature itself, as well as for improved determination of $T_{eff}$ from the $H_{\alpha}$ and $H_{\beta}$ profiles, will provide a useful constraint on the possible scenarios proposed to explain the Li problems. Moreover, measurements of Li abundances for even lower metallicity stars ([Fe/H] < −3.5) are also vital. Measurements of Li abundances in this metallicity range have been reported so far only for one system, a double-lined spectroscopic binary (CS 22876−032: Norris et al. 2000; González Hernández et al. 2008). We plan additional investigations of this metallicity range by high-resolution spectroscopic studies of EMP star candidates discovered by the Hamburg/ESO survey and SDSS/SEGUE in the near future.

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REFERENCES

Alonso, A., Arribas, S., & Martínez-Roger, C. 1996, A&A, 313, 873
Andrievsky, S. M., Spite, M., Korotin, S. A., Spite, F., Bonifacio, P., Cayrel, R., Hill, V., & François, P. 2007, A&A, 464, 1081
Aoki, W., et al. 2005, A&A, 432, 611
Aoki, W., et al. 2006, ApJ, 639, 897
Aoki, W., et al. 2008, ApJ, 678, 1351
Asplund, M. 2005, ARA&A, 43, 481
Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in ASP Conf. Ser. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, ed. T. G. Barnes III & F. N. Bash (San Francisco, CA: ASP), 25
Beers, T. C., Chiba, M., Yoshii, Y., Platais, I., Hansson, R. B., Fuchs, B., & Rossi, S. 2000, AJ, 119, 2866
Beers, T. C., et al. 2007, ApJS, 168, 128
Boesgaard, A. M., Stephens, A., & Deliyannis, C. P. 2005, ApJ, 633, 398
Bonifacio, P., et al. 2007, A&A, 470, 153
Carollo, D., et al. 2007, Nature, 450, 1020
Castelli, F., & Kurucz, R. L. 2003, in Proc. IAU Symp. 210, Modelling of Stellar Atmospheres, ed. N. Piskunov, W. W. Weiss, & D. F. Gray (San Francisco, CA: ASP), 20
Coc, A., Vangioni-Flam, E., Descouvemont, P., Adahchour, A., & Angulo, C. 2004, ApJ, 600, 544
Cyburt, R. H., Fields, B. D., & Olive, K. A. 2008, arXiv:0808.2818
Frebel, A., Collet, R., Eriksson, K., Christlieb, N., & Aoki, W. 2008, ApJ, 684, 588
Frebel, A., et al. 2005, Nature, 434, 871
Fuhrmann, K., Acker, M., & Gehren, T. 1993, A&A, 271, 451
González Hernández, J. I., & Bonifacio, P. 2009, A&A, 497, 497
González Hernández, J. I., et al. 2008, A&A, 480, 233
Hosford, A., Ryan, S. G., García Pérez, A. E., Norris, J. E., & Olive, K. A. 2009, A&A, 493, 601
Kim, Y.-C., Demarque, P., Yi, S. K., & Alexander, D. R. 2002, ApJS, 143, 499
Korn, A. J., Grundahl, F., Richard, O., Barklem, P. S., Mashonkina, L., Collet, R., Piskunov, N., & Gustafsson, B. 2006, Nature, 442, 657
Korn, A. J., Grundahl, F., Richard, O., Mashonkina, L., Barklem, P. S., Collet, R., Gustafsson, B., & Piskunov, N. 2007, ApJ, 671, 402
Korn, A. J., Richard, O., Mashonkina, L., Bessell, M. S., Frebel, A., & Aoki, W. 2009, ApJ, in press (arXiv:0903.3885)
Kurucz, R. L. 1993, Cd-rom 13, Atlas9 Stellar Atmospheres Programs and 2 km/s Grid (Cambridge: Smithsonian Astrophys. Obs.)
Munari, U., & Zwitter, T. 1997, A&A, 318, 269
Nissen, P. E., Akerman, C., Asplund, M., Fabbian, D., & Pettini, M. 2005, in Proc. IAU Symp. 228, From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution, ed. V. Hill, P. François, & F. Primas (Cambridge: Cambridge Univ. Press), 101
Noguchi, K., et al. 2002, PASJ, 54, 855
Norris, J. E., Beers, T. C., & Ryan, S. G. 2000, ApJ, 540, 456
Norris, J. E., Ryan, S. G., & Beers, T. C. 2001, ApJ, 561, 1034
Pasquini, L., Bonifacio, P., Molaro, P., François, P., Spite, F., Gratton, R. G., Carretta, E., & Wolff, B. 2005, A&A, 441, 549
Piau, L., Beers, T. C., Balsara, D. S., Sivarani, T., Truran, J. W., & Ferguson, J. W. 2006, ApJ, 653, 504
Ramírez, I., & Meléndez, J. 2005a, ApJ, 626, 446
Ramírez, I., & Meléndez, J. 2005b, ApJ, 626, 445
Ryan, S. G., Beers, T. C., & Deliyannis, C. P., & Thorburn, J. A. 1996, ApJ, 458, 543
Ryan, S. G., Gregory, S. G., Kolb, U., Beers, T. C., & Kajino, T. 2002, ApJ, 571, 501
Ryan, S. G., Norris, J. E., & Beers, T. C. 1999, ApJ, 523, 654
Schlegel, D., Finkbeiner, D., & Davis, M. 1998, ApJ, 500, 525
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Smit, H. C., Lamberts, D. L., & Nissen, P. E. 1998, ApJ, 500, 408
Spelg, D. N., et al. 2003, ApJ, 148, 175
Spite, M., & Spite, F. 1982, Nature, 297, 483
Steihl, C., & Huchene, R. 1999, A&AS, 140, 93
Takeda, Y., Zhao, G., Takada Hidai, M., Chen, Y.-Q., Saito, Y.-J., & Zhang, H.-W. 2003, Chin. J. Astron. Astrophys., 3, 316
Travaglio, C., Gallino, R., Arnone, E., Cowan, J., Jordan, F., & Sneden, C. 2004, ApJ, 601, 864
Truran, J. W., Cowan, J. J., Pilachowski, C. A., & Sneden, C. 2002, PASP, 114, 1293
Tsujii, T. 1978, A&A, 62, 29
Zacharias, N., Monet, D. G., Levine, S. E., Urban, S. E., Gaume, R., & Wycoff, G. L. 2004, BAAS, 36, 1418