High-resolution Spectroscopy of Extremely Metal-poor Stars from SDSS/SEGUE. III.  
Unevolved Stars with [Fe/H] ≲ −3.5

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Abstract

We present elemental abundances for eight unevolved extremely metal-poor (EMP) stars with $T_{\text{eff}} > 5500$ K, among which seven have [Fe/H] < −3.5. The sample is selected from the Sloan Digital Sky Survey/Sloan Extension for Galactic Understanding and Exploration (SDSS/SEGUE) and our previous high-resolution spectroscopic follow-up with the Subaru Telescope. Several methods to derive stellar parameters are compared, and no significant offset in the derived parameters is found in most cases. From an abundance analysis relative to the standard EMP star G64–12, an average Li abundance for stars with [Fe/H] < −3.5 is $A(\text{Li}) = 1.90$, with a standard deviation of $\sigma = 0.10$ dex. This result confirms that lower Li abundances are found at lower metallicity, as suggested by previous studies, and demonstrates that the star-to-star scatter is small. The small observed scatter could be a strong constraint on Li-depletion mechanisms proposed for explaining the low Li abundance at lower metallicity. Our analysis for other elements obtained the following results: (i) a statistically significant scatter in [X/Fe] for Na, Mg, Cr, Ti, Sr, and Ba, and an apparent bimodality in [Na/Fe] with a separation of ~0.8 dex, (ii) an absence of a sharp drop in the metallicity distribution, and (iii) the existence of a CEMP- star at [Fe/H] ≃ −3.6 and possibly at [Fe/H] ≈ −4.0, which may provide a constraint on the mixing efficiency of unevolved stars during their main-sequence phase.

Key words: Galaxy: halo – stars: abundances – stars: atmospheres – stars: Population II

Supporting material: machine-readable table

1. Introduction

Extremely metal-poor (EMP; [Fe/H] < −3.0) stars provide chemical information on the universe at a unique phase of its evolution. Precise measurements of the cosmic microwave background (CMB) from space constrain the conditions at the time of the Big Bang (e.g., Planck Collaboration et al. 2016), whereas observations of galaxies across a wide range of redshift trace galaxy evolution over cosmic time (e.g., Madau & Dickinson 2014). However, in order to connect galaxy formation with the Big Bang, understanding of the formation and evolution of first-generation stars is indispensable. Since the chemical abundances of EMP stars are not generally affected by nucleosynthesis processes other than the Big Bang and the supernovae explosions of the first stars, they can fill the gap between observations of the CMB and those of later-forming galaxies.

Stellar Li abundances deliver uniquely important information, since Li is the only element (beyond H and He) that is synthesized in the Big Bang to a significant degree and can be measured in the atmospheres of many EMP stars. Although the constant Li abundance found in metal-poor turnoff stars was formerly regarded as a constraint on Big Bang nucleosynthesis (Spite & Spite 1982a, 1982b), the “Li plateau” value turned out to stand in contradiction to the Li abundance predicted by Big Bang nucleosynthesis models based on recent CMB observations (Coc et al. 2004; Cyburt et al. 2016). Theoretical trials invoking Li-depletion mechanisms in the formation and evolution of low-mass metal-poor stars have attempted to explain this discrepancy (e.g., Richard et al. 2005; Piau et al. 2006; Fu et al. 2015). One difficulty is reproducing the small observed scatter in Li abundances for metal-poor turnoff stars with $−2.5 < [\text{Fe/H}] < −1.6$. In addition, recent observations demonstrate that the plateau breaks down below [Fe/H] ≃ −2.5, and no star has Li abundance comparable to the plateau below [Fe/H] = −4.0 (e.g., Ryan et al. 1996, 1999; Bonifacio et al. 2007, 2015; Frebel et al. 2008; Aoki et al. 2009; Sbordone et al. 2010; Caffau et al. 2011; Hansen et al. 2014; Li et al. 2015).

The key stellar metallicity occurs below [Fe/H] ≃ −3.0, especially $< −3.5$. Stars with [Fe/H] ≃ −3.5 bridge the Spite Plateau stars and ultra metal-poor (UMP; [Fe/H] < −4.0) stars, all of which exhibit low lithium abundances. However, the current sample size of turnoff stars with $−4.0 < [\text{Fe/H}] < −3.5$ with available Li measurements is still small, ~10 according to the SAGA database (Suda et al. 2008, 2011; Yamada et al. 2013).

One of the reasons for the small sample size is the rarity of EMP stars. Another is the difficulty of deriving precise abundances for warm EMP stars. In addition to their extremely low metallicity, the relatively high temperatures of main-sequence turnoff stars weaken their absorption lines; higher signal-to-noise ratios (S/Ns) for such stars are required for precise abundance measurements.

The purpose of this study is to determine chemical abundances, including Li, for turnoff stars with [Fe/H] < −3.5.
We have obtained high-resolution, high-S/N spectra with the Subaru Telescope for eight warm EMP stars ($T_{\text{eff}} > 5500$ K, $[\text{Fe/H}] < -3.0$) previously considered by Aoki et al. (2013); seven of the eight have $[\text{Fe/H}] < -3.5$. The relatively narrow range of stellar parameters among the sample enables a high-precision differential abundance analysis. Hence, besides understanding of the nature of possible Li-depletion mechanisms, these targets are useful for investigation of other elemental abundances for EMP stars. In addition, since our targets have not yet reached the red giant stage of evolution, we can examine possible abundance changes caused by first dredge-up (e.g., Spite et al. 2006) from a comparison of the chemical abundances of our targets with those of red giants reported in the literature.

This paper is organized as follows. Details of target selection and observation are described in Section 2. In Section 3, we compare several methods to derive stellar parameters for the eight targets. In addition, we also determine stellar parameters for two bright EMP main-sequence stars (G 64–12 and LP 815–43) with parallaxes measured by the Gaia satellite. The abundance analysis and its results are described in Section 4. After presenting an interpretation of the results in Section 5, we summarize our conclusions in Section 6.

2. Observations and Reduction

The targets in our present study are selected from Aoki et al. (2013), who reported the results of abundance analysis of snapshot high-resolution spectroscopy for 137 metal-poor candidates discovered by the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009). We have obtained new, higher-quality spectra for eight targets with the High Dispersion Spectrograph on the Subaru Telescope (Noguchi et al. 2002). The spectral resolution is $R = 60,000$ with $2 \times 2$ CCD binning; the wavelength coverage is 3800–6000 Å. Details of the observations are provided in Table 1. Hereafter, object names are shown using abbreviations, e.g., SDSS J0120–1001 for SDSS J012032.63–100106.5. Although the spectrum of one of our targets, SDSS J1424+5615, has been analyzed in Matsuno et al. (2017), we reanalyze it in this study.

The data are reduced in a standard manner using the IRAF6 echelle package, including bias correction, flat fielding, scattered light subtraction, extraction of spectra, and wavelength calibration using Th arc lines. The S/Ns per 1.1 km s$^{-1}$ pixel around 7608 Å and per 1.5 km s$^{-1}$ around 4877 Å (after rebinning) are estimated from the standard deviation of the continuum level. Heliocentric radial velocities ($v_r$) are estimated from Fe lines. Typical uncertainties in $v_r$ are ±1 km s$^{-1}$. All targets but one show no significant changes in radial velocity from Aoki et al. (2013). The exception is SDSS J2349+3832, for which our radial velocity is larger than that of the epoch of 2008 August 22 by 3.1 km s$^{-1}$.

We also analyze the spectra of two bright EMP main-sequence turnover stars, G 64–12 ([Fe/H] = −3.38) and LP 815–43 ([Fe/H] = −2.96). The spectrum of G 64–12 was taken on 2002 December 22 with $R \sim 90,000$ and S/N $\sim 650$ at 7608 Å (S/N $\sim 454$ at 4880 Å) (Aoki et al. 2009). The spectrum of LP 815–43, which was taken from the Subaru archive SMOKA (Baba et al. 2002), was originally obtained on 2005 May 18 with $R \sim 90,000$ and S/N $\sim 260$ at 7608 Å (S/N $\sim 142$ at 4880 Å). Both stars are included in the first data release of the Gaia satellite (Gaia Collaboration et al. 2016a, 2016b), which allows us to obtain an independent determination of their surface gravities.

3. Stellar Atmospheric Parameters

3.1. Methods

In order to establish the most reliable method to derive stellar parameters for EMP turnover stars, we apply four methods: (i) analysis of Balmer-line profiles, (ii) spectroscopic analysis of Fe lines, (iii) the SEGUE Stellar Parameter Pipeline (SSPP; Allende Prieto et al. 2008; Lee et al. 2008a, 2008b), and (iv) colors (only for $T_{\text{eff}}$); and we compare the results. Each method is briefly described below.

3.1.1. Balmer-line Profiles

Balmer lines of hydrogen are prominent in spectra of warm stars. Their profiles, especially the width of the wings, are sensitive to effective temperature. Contamination arising from metallic absorption lines in the profiles of Balmer lines is insignificant in EMP stars, with the exception of the Hγ line in carbon-enhanced metal-poor (CEMP) stars, which can be impacted by the presence of the CH G-band molecular feature. Our procedure is essentially the same as the method of Barklem et al. (2002), and is described in Matsuno et al. (2017). We briefly summarize our approach here, focusing on differences from the previous work.

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6 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.
Careful continuum placement is essential in the analysis of Balmer lines with broad profiles. We estimate the continuum level by interpolating across the blaze functions of adjacent orders containing these lines. Models of Balmer-line profiles are taken from interpolation of the grid by Barklem et al. (2002).³ Atmospheres with \([\text{Fe}/\text{H}] = -3\) and \([\alpha/\text{Fe}] = +0.4\) are assumed throughout the analysis. While the \(H\beta\) line is only sensitive to \(T_{\text{eff}}\), \(H\alpha\) is also dependent on surface gravity, \(\log g\). Hence, we determine \(T_{\text{eff}}\) from the \(H\beta\) line first, assuming \(\log g = 4.0\), and then determine \(\log g\) from the \(H\alpha\) line. We iterate the estimates until the set of \((T_{\text{eff}}, \log g)\) reaches convergence (usually less than three times). Once we obtain the best-fit spectrum from the \(H\beta\) and \(H\alpha\) fitting procedure, we remove possible effects of cosmic rays and absorption lines from the observed spectrum by masking pixels that deviate from the best-fit spectrum by more than 2.5\(\sigma\). We also modify the fitting region to include only the line wings, defined as the regions where the normalized flux of the best-fit model is between 0.7 and 0.9. We then repeat the fitting until convergence is achieved (usually less than five times).

Errors in our procedure are dominated by uncertainty of the continuum placement. An error of 0.5% in the continuum placement for our sample stars is estimated by applying the interpolating procedure to the orders that contain no broad absorption features. We estimate its effect on \(T_{\text{eff}}\) and \(\log g\) by analyzing the spectra whose continuum level is artificially shifted by 0.5%. In addition, since the estimate of surface gravity is dependent on the assumed \(T_{\text{eff}}\), we calculated uncertainties of \(\log g\) as follows:

\[
\sigma_{\log g}^2 = (\delta \log g)^2 + \left(\frac{\partial \log g}{\partial T_{\text{eff}}} \delta T_{\text{eff}}\right)^2,
\]

where \(\delta X\) represents the uncertainties caused by errors in continuum placement, \(\sigma_X\) is the total uncertainties, and \(X\) denotes either \(\log g\) or \(T_{\text{eff}}\). Since \(\log g\) does not affect estimates of \(T_{\text{eff}}\), we adopt \(\sigma_{\log g} = \delta T_{\text{eff}}\). The covariance can be found in a similar manner:

\[
\sigma_{\log g \log g} = \frac{\partial \log g}{\partial T_{\text{eff}}} \sigma_{T_{\text{eff}}}^2.
\]

Since covariances contribute to the total errors of our derived abundances, they need to be taken into account.

We finally check the fitting results by eye. The fitting results for SDSS J1424+5615 are shown in Figure 1.

Although the microturbulent velocity \(v_t\) is not required for the Balmer-line analysis, it needs to be determined for the abundance analysis. The microturbulent velocity is not derived from the Balmer-line profiles, but is determined so that abundances derived from individual neutral Fe lines exhibit no trends with the strengths of the lines. The uncertainty of \(v_t\), expressed as \(\delta v_t\), is determined so that the trend is not significant at greater than the 1\(\sigma\) level. In addition, we also examine the uncertainties of \(v_t\) due to the errors in \(T_{\text{eff}}\) and \(\log g\).

### 3.1.2. Fe-lines Method

This method determines stellar parameters from an analysis of Fe absorption lines in a spectrum, those that result in no dependence on the ionization stage, excitation potential, or strength of the individual lines.

Suppose that \(E_W\) is the equivalent width of an Fe line and \(A_i\) is the Fe abundance determined from the line. In order to determine stellar parameters, we evaluate three probabilities:

1. \(p_{\text{ex}}\): Probability that the correlation between completely uncorrelated sets of values becomes larger than the observed correlation between \(A_i\) and excitation energy.
2. \(p_{\text{ion}}\): Probability that a difference between Fe abundances determined from neutral species and ionized species becomes larger than the observed difference due only to measurement errors.
3. \(p_{\text{ew}}\): Probability that a correlation between completely uncorrelated sets of values becomes larger than the observed correlation between \(A_i\) and the normalized equivalent width, \(\log(EW/\lambda)\).

The probabilities \(p_{\text{ex}}\) and \(p_{\text{ew}}\) are evaluated using Spearman’s rank correlation test. This is because the expected correlations are not necessarily linear, especially that between \(\log(EW/\lambda)\) and \(A_i\). Then, we search for the combination of stellar parameters \((T_{\text{eff}}, \log g, v_t)\) that maximizes \(p = p_{\text{ex}}p_{\text{ion}}p_{\text{ew}}\). The \([\text{Fe}/\text{H}]\) of the model atmosphere is also forced to agree with the derived \([\text{Fe}/\text{H}]\) within 0.3 dex.

Uncertainties are estimated using a confidence-region boundary, where \(p = 0.317p_{\text{max}}\), assuming it to be a 3D ellipsoid. Covariances of any pair of the three parameters are also estimated.

Determination of stellar parameters from Fe lines relies wholly on model atmospheres, and could be significantly affected by deviation from local thermodynamic equilibrium (non-LTE, NLTE) and the effect of 3D motions in the atmosphere. The NLTE/3D effects might be significantly large for EMP stars (Asplund 2005). In a limited range of \(T_{\text{eff}}\) and \([\text{Fe}/\text{H}]\), however, the correction should be systematic. For example, the difference between the Fe abundance derived from an NLTE analysis of the Fe I lines and that from an LTE analysis varies less by than 0.1 dex within the parameter range of our targets (Lind et al. 2012). In order to avoid such systematic effects, we carry out a line-by-line differential analysis and adopt a well-studied bright EMP turnoff star, G64–12, as a reference star. For each line, we first determine the difference in abundance \((\Delta A_i)\) between the target and G64–12, and then convert it to the abundance of the star \(A_i\) by using

\[
A_i = (A_{\text{G64}} - 12) + \Delta A_i.
\]

### 3.1.3. Stellar Parameter Estimates Based on SSPP, Color, and Parallax

Effective temperatures estimated by the SSPP, and given in Data Release 7 (DR7) of the SDSS, were adopted by Aoki et al. (2013) for their sample of stars, from which our targets are selected. However, updates to the SSPP have continued, so here we adopt estimates of \(T_{\text{eff}}\) and \(\log g\) derived by using the latest version. The update results in higher \(T_{\text{eff}}\) by ~100 K.

We also derive effective temperatures from photometric colors, for a comparison of stellar parameters estimated by different methods. We first convert \(g\), \(r\), and \(i\)-band \(psfMag\) measured in the SDSS survey to the Johnson–Cousins \(B\), \(V\), \(R_c\), and \(I_c\) system using the formulae provided by Jordi et al. (2006) for Population II stars. Since SDSS photometry of

³ http://www.astro.uu.se/%7ebarklem/
G64–12 and LP 815–43 suffers from saturation, we adopt the APASS \( V \) magnitudes for these two targets (Henden et al. 2016). Infrared photometric data are taken from the Two-Micron All-Sky Survey (2MASS; Cutri et al. 2003). After correcting for extinction according to Schlafly & Finkbeiner (2011), we derive effective temperatures from \( V - K_s \) colors using the calibration of Casagrande et al. (2010), with the assumption of \([\text{Fe}]/\text{H}]=-3.5\). These two methods are based on calibrations using bright and/or nearby standard stars to establish the scale. Since EMP turnoff stars are rare, the uncertainties could be larger than those for less metal-poor stars.

The stars G64–12 and LP 815–43 are both included in the Data Release 1 of \textit{Gaia}. We calculated their luminosities using the \textit{Gaia} parallaxes, the bolometric correction of Casagrande et al. (2010), and \( V_-\) and \( K_-\)-band magnitudes. Surface gravity is then derived from the following equation:

\[
\log g = \log g_\odot + \log\left(\frac{M}{M_\odot}\right) + 4\log\left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}}\right) - \log\left(\frac{L}{L_\odot}\right),
\]

where \( M \) is the mass of the stars, assumed to be 0.75 \( M_\odot \), and \( L \) is their luminosity. We adopt \( \log g_\odot = 4.438 \) and \( T_{\text{eff},\odot} = 5777 \) K as the solar values.

### 3.2. Results

#### 3.2.1. Results for Bright EMP Stars

Before discussing our SDSS program stars, we present results for G64–12 and LP 815–43, as a check on both the absolute and relative scales of the derived stellar parameters in this work. Note that LP 815–43 is analysed only for the evaluation of the relative scale, and is not included in the subsequent abundance analysis.

Stellar parameter estimates for G64–12 and LP 815–43 are summarized in Table 2. They are also shown in Figures 2 and 3. We note that the result for the Balmer-line analysis of G64–12 is slightly different from that in our previous work (Matsumo et al. 2017), due to small changes in the algorithm. The difference is still within the quoted uncertainty.

Results from the Balmer-line profile analysis agree with those obtained from the analysis of Fe lines within the errors.

On the other hand, there appears to be a systematic difference of 100–150 K between the Balmer-line estimates of \( T_{\text{eff}} \) and the color-based ones (Aoki et al. 2006; Norris et al. 2013a). A high-precision analysis of G64–12 has been carried out in previous studies (Placco et al. 2016; Reggiani et al. 2016) and obtained \( T_{\text{eff}} = 6463 \) K (Meléndez et al. 2010) and \( \log g = 4.26 \) (Nissen et al. 2007). While our temperature estimate based on the Balmer-line analysis is lower than theirs, our color-based estimate is consistent. See Matsumo et al. (2017) for a detailed comparison among derived effective temperatures of G64–12 in previous studies.

Since a differential analysis is conducted in this work, the differences in the estimated parameters between a target star and the reference star (G64–12) are important. The symbol “\( \Delta \)”

**Figure 1.** Fitting results for the H\( \beta \) line (left panel) and H\( \alpha \) line (right panel) of SDSS J1424+5615. Red points show the observed normalized spectrum and the blue line shows the best-fit model spectrum. To avoid the effects of cosmic rays and/or absorption lines, and to perform the fitting of the line wings, the gray shaded regions are excluded from the fitting procedure (see text for details).

**Table 2.** Comparison of Stellar Parameters for G64–12 and LP 815–43

| Method    | Parameter | G64–12 | LP 815–43 | \( \Delta \) |
|-----------|-----------|--------|-----------|-------------|
| Balmer lines | \( T_{\text{eff}} \) (K) | 6285 | 6323 | 38 |
|           | \( \sigma_{T_{\text{eff}}} \) (K) | 26 | 31 | 40 |
|           | \( \log g \) | 4.30 | 4.21 | –0.09 |
|           | \( \sigma_{\log g} \) | 0.15 | 0.17 | 0.23 |
|           | \( v_t \) (km s\(^{-1}\)) | 1.32 | 1.62 | 0.30 |
|           | \( \sigma_v \) (km s\(^{-1}\)) | 0.18 | 0.19 | 0.26 |
| Fe lines\(^b\) | \( T_{\text{eff}} \) (K) | (6285) | 6424 | 139 |
|           | \( \sigma_{T_{\text{eff}}} \) (K) | … | 83 | 79 |
|           | \( \log g \) | (4.30) | 4.22 | –0.08 |
|           | \( \sigma_{\log g} \) | … | 0.20 | 0.13 |
|           | \( v_t \) (km s\(^{-1}\)) | (1.32) | 1.54 | 0.22 |
|           | \( \sigma_v \) (km s\(^{-1}\)) | … | 0.17 | 0.09 |
| Color (\( V - K_s \)) | \( T_{\text{eff}} \) (K) | 6434 | 6481 | 47 |
|           | \( \sigma_{T_{\text{eff}}} \) (K) | 55 | 67 | 87 |
| Parallax | \( \log g \) | 4.23 | 4.15 | –0.08 |
|           | \( \sigma_{\log g} \) | 0.16 | 0.13 | 0.21 |

**Notes.**

\(^a\) Errors in \( \Delta \) for the stellar parameters are quadratic sums of the errors for the individual stars, except for the Fe-lines method, for which errors of LP 815–43 are the quadratic sums of the errors of G64–12 and the error in \( \Delta \).

\(^b\) Spectroscopic parameters are determined using G64–12 as a reference star, using the listed parameters for this star.
and ages of 0 and 12, 14 Gyr, which are shown as dot-dashed, solid, and dashed yellow lines, respectively (Kim et al. 2002). The results of the analysis of Balmer-line profiles are shown with blue filled circles, those of the analysis of Fe lines are shown with red squares, and those of the SSPP are shown with green crosses. Results for the same star are connected with black lines, and 1σ uncertainties are shown with ellipses. The result of the Balmer-line analysis for G64–12 is shown with a blue star. LP 815–43 is shown with open symbols. The SDSS program stars are shown with filled symbols.

Figure 2. Stellar parameters for our program stars in an H–R diagram, together with α-enhanced J9 isochorones with [Fe/H] = −3.0 and ages of 10, 12, and 14 Gyr, which are shown as dot-dashed, solid, and dashed yellow lines, respectively (Kim et al. 2002). The results of the analysis of Balmer-line profiles are shown with blue filled circles, those of the analysis of Fe lines are shown with red squares, and those of the SSPP are shown with green crosses. Results for the same star are connected with black lines, and 1σ uncertainties are shown with ellipses. The result of the Balmer-line analysis for G64–12 is shown with a blue star. LP 815–43 is shown with open symbols. The SDSS program stars are shown with filled symbols.

listed in Table 2 describes this difference for parameters derived for G64–12 and LP 815–43. The effective temperature of LP 815–43 determined by each method is slightly higher than that of G64–12, whereas log g of LP 815–43 is slightly lower than that of G64–12. We conclude that relative differences of parameters are not so affected by the choice of methods, even though a small offset exists between individual methods.

3.2.2. Results for the SDSS Sample

Results for our program sample of SDSS stars are summarized in Table 3 and shown in Figure 2. Two out of the eight stars contain only a small number of Fe absorption lines, and thus are not suitable for spectroscopic determination of stellar parameters from Fe lines. For two other stars, the set of stellar parameters that simultaneously satisfy the three requirements listed in Section 3.1.2 above are not found. The results based on the analysis of Fe lines for these four stars are excluded from Table 3.

A comparison of the results obtained by the different methods we consider is presented in Figures 2 and 3. As can be seen, in most cases, the parameters from the analysis of Fe lines are in agreement with those from the Balmer-line profiles within the uncertainties, though the errors are large. We note that no offset is expected due to the differential analysis. On the other hand, there is a systematic difference in $T_{\text{eff}}$ between the SSPP-based estimates and the Balmer-line analysis, which could be related to the known difference between $T_{\text{eff}}$ from Balmer-line analysis and photometric estimates of $T_{\text{eff}}$ (Norris et al. 2013a). We note that Aoki et al. (2013) adopted values of $T_{\text{eff}}$ estimated by a previous version of SSPP that are systematically lower than the present one. Hence, the difference between our results of the Balmer-line analysis and those of Aoki et al. (2013) is smaller by about 100 K than the difference between Balmer-line analysis and the current version of SSPP.

Contrary to what was found from the analysis of G64–12 and LP 815–43, we do not find any systematic difference in estimates of effective temperature between the Balmer-line analysis and $V - K_s$ color approach. Although Aoki et al. (2013) reached the conclusion that the offset in $T_{\text{eff}}$ between $V - K_s$ color and the SSPP is small for their sample with [Fe/H] < −2.5, the latest version of the SSPP appears to overestimate $T_{\text{eff}}$ compared to the $V - K_s$ color technique for EMP turnoff stars. There is also a difference between the dust map adopted to correct for interstellar extinction between the present analysis and that used by Aoki et al. (2013). We note that the comparison here includes only a small sample in the present study, and that the $T_{\text{eff}}$ derived from colors could be affected by large errors in the $K_s$-band magnitude of 2MASS for these fainter stars.

Uncertainties in the Balmer-line analysis are dominated by the continuum placement, which does not significantly depend on S/N for our sample stars. Therefore, we adopt the results derived from the analysis of Balmer-line profiles in the abundance analysis described below. The Balmer-line analysis failed to determine log g for SDSS J0120–1001, due to the limited range of the grid (for $T_{\text{eff}} \geq 5600$ K, only log g ≥ 3.4 is covered). In addition, the log g sensitivity of Hα lines dramatically decreases at log g ≤ 3.4. Considering the similarity of the SSPP log g between SDSS J1036+1212, SDSS J1522+3055, and SDSS J0120–1001, we adopt log g = 3.4 ± 0.3 for the abundance analysis of this star.

Behara et al. (2010) also analyzed our program star SDSS J1036+1212. Their $T_{\text{eff}}$ estimate is based on the Hα wing, and the log g estimate is based on ionization balance between Fe I and Fe II. They obtained $T_{\text{eff}} = 6600$ K and log g = 4.0, which are ~500 K and 0.3 dex higher than our results. The $T_{\text{eff}}$ derived from the $V - K_s$ color is somewhat closer, but still 300 K cooler than their result. The source of the difference is not clear, because their methods and ours are similar. There is another discrepancy between the present study and Behara et al. (2010). It concerns the Eu abundance and is discussed in Section 5.4.

The adopted microturbulent velocities are listed in Table 4. For SDSS J2309+2308 and SDSS J2005–1045, $v_t$ is not well constrained due to the small number of Fe absorption lines in these spectra. We adopt $v_t = 1.0 \pm 0.5$ km s$^{-1}$ for these targets.
4. Chemical Abundances

4.1. Abundance Analysis

We use 1D LTE model atmospheres from the ATLAS NEWOFD grid with [α/Fe] = +0.4 (Castelli & Kurucz 2003) in the abundance analysis. Abundances are determined differentially with respect to the reference star G64–12, as described in Section 3.1.2.

The line list used in the present work is based on that of Aoki et al. (2013), updated to include recently published gf-values. We then restrict the list to the lines identified in the spectrum of G64–12. Because of a slight difference in instrument setting, our spectrum of G64–12 does not cover wavelengths shorter than 4100 Å. In order to efficiently utilize the spectra of the SDSS sample, we also include Mn I 4044 Å, Fe I 4046 Å, Fe I 4058 Å, Sr II 4064 Å, and Sr II 4078 Å, whose equivalent widths for G64–12 are taken from Reggiani et al. (2016).

The equivalent width of each absorption line is measured by Gaussian fitting and listed in Table 5. The continuum level is estimated by comparing the spectrum of the targets with that of G64–12. The widths of the absorption lines are dominated by instrumental broadening and macroturbulence, and exclude the possibility of rapid rotation for our sample stars.

In addition, we include the line list for the CH G-band from Masseron et al. (2014) and the line list of 3Li from Smith et al. (1998). We determine abundances from spectrum synthesis using 4222.8–4325.4 Å for the CH G-band and 6707.4–6708.2 Å for the Li I doublet.

We adopt the mean of the abundances determined from individual lines for each species. Uncertainties are determined as follows:

\[
\sigma(X) = \sqrt{\sigma_{\text{lines}}^2/N + \sigma_{\text{atm}}^2},
\]

where \(\sigma_{\text{lines}}\) is the standard deviation of abundances determined from individual lines, and \(N\) is the number of lines used in the analysis. When \(N < 3\), we take \(\sigma_{\text{Fe}}\) as \(\sigma_{\text{lines}}\). The variable \(\sigma_{\text{atm}}\) is the uncertainty due to uncertainties in the estimates of stellar parameter expressed as

\[
\sigma_{\text{atm}}^2 = \sum_{i=1}^{4} \left( \frac{\partial \log \epsilon}{\partial X_i} \sigma_{\epsilon X_i} \right)^2 + \sum_{i \neq j} \frac{\partial \log \epsilon}{\partial X_i} \frac{\partial \log \epsilon}{\partial X_j} \sigma_{X_i X_j},
\]

where \((X_1, X_2, X_3, X_4) = (T_{\text{eff}}, \log g, v_t, [\text{Fe/H}])\).

In cases where no absorption lines are detected for a specific element, we place conservative \(5\sigma\) upper limits on the equivalent widths, so that the upper limits on equivalent widths do not contradict with the equivalent widths of lines that are detected in the spectrum. These \(5\sigma\) upper limits are also placed on Li and C abundances from spectral synthesis.

Note that our analysis is carried out differentially on the scale of G64–12. Therefore, when one compares the abundances with other papers, it is required to include the uncertainty in abundances of G64–12. In particular, NLTE could significantly affect some elements, and 3D effects may play a major role in the strengths of the molecular lines.

4.2. Results

Results of the abundance analysis are listed in Table 6 (metallicities are listed in Table 4). The results are also displayed in Figure 4. Note that the metallicities for all but one of our program stars (seven of eight) are \([\text{Fe/H}] < -3.5\). The stars G64–12 and SDSS J1424+5615 have been previously analyzed in Matuno et al. (2017). As the line list and some algorithms employed have been updated, the derived abundances for these stars are not exactly the same. The difference is \(\lesssim 0.05\) dex for G64–12 and \(\lesssim 0.2\) dex for SDSS J1424+5615 (~0.4 dex for [C/Fe]). The larger difference for SDSS J1424+5615 is because we derive abundances differentially in this study. Note that we are able to derive a C abundance estimate for G64–12, which was not derived in Matuno et al. (2017). Although the redder part of the fitting region in our spectrum is significantly affected by bad columns
in the CCD, the bluer part turns out to have sufficiently high quality to derive a C abundance ($\leq 4324.5$ Å). The carbon ([C/Fe] = +0.92) and barium ([Ba/Fe] = −0.07) abundance ratios of G64–12 are consistent with its classification as a CEMP star with no enhancement of neutron-capture elements (CEMP-no; Beers & Christlieb 2005), if we adopt $[C/Fe] > +0.7$ as the CEMP criterion (Placco et al. 2016).

Whereas $\log g$ estimates in most previous studies are determined from ionization balance of FeI and FeII lines, here we adopt $\log g$ estimated from Balmer-line profiles. We detect FeII lines for seven objects, for all of which the difference in Fe abundances from FeII lines and from FeI lines is consistent with the difference of G64–12 (0.11 dex) within 2σ, and for five of which the differences are within 1σ (Figure 4). This result indicates that the abundance results of the present work do not change essentially even if $\log g$ is estimated from an FeI/II balance.

### 4.2.1. Carbon

Two stars in our SDSS program sample exhibit significant carbon enhancement ([C/Fe] > +1.0). One is SDSS J1036+1212 ([C/Fe] = +1.19) with a high Ba abundance ([Ba/Fe] = +1.68). The metallicity of this star is $[\text{Fe/H}] = -3.62$, which makes it one of the most metal-poor CEMP-s stars (CEMP stars with s-process enhancements; Beers & Christlieb 2005). The Sr abundance of this star is low, which is a characteristic feature of CEMP-s stars. Although the abundances of SDSS J1036+1212 derived in this work and those derived by Behara et al. (2010) differ, due to different choices of effective temperature, high C, high Ba, and low Sr abundances are obtained by both studies. The other CEMP star is SDSS J1424+5615, which has been studied in Matsuno et al. (2017). Interestingly, both stars show large Na enhancements (Table 6).

There is another star, SDSS J2309+2308, that exhibits Na and Ba excesses, although its Ba abundance relies on only one BaII line at 4554 Å. This object could also be a CEMP-s star. The upper limit on C ([C/Fe] < +2.0) is insufficient to determine whether this star is C-rich or not. The reported upper limits on C abundance for most of our SDSS program stars are not sufficiently low to identify them as C-normal stars.

Although Eu abundances for the C-rich stars are important to identify “CEMP-i” stars (Hampel et al. 2016), the relatively high temperatures of our SDSS program stars prevent determination of meaningful limits for their Eu abundances based on our present data.

#### 4.2.2. Lithium

The Li abundance we obtain for G64–12 places it on the Spite Plateau, similar to those reported by previous studies, confirming that our analysis is consistent in the framework of 1D LTE analysis. SDSS J1424+5615, which has the highest metallicity among stars in our sample ([Fe/H] = −3.10), has a comparable Li abundance to G64–12. By contrast, all stars with $[\text{Fe/H}] < -3.5$ in our sample have Li abundances less than $A(\text{Li}) = 2.0$. This extends the previously found decreasing trend of lithium toward the lowest metallicity to $[\text{Fe/H}] ~ 4$ (Bonifacio et al. 2007; Aoki et al. 2009; Sbordone et al. 2010). The Li abundances are compared with previous studies and discussed in detail in Section 5.

### 5. Discussion

#### 5.1. Lithium Abundances of Extremely Metal-poor stars

The Li abundances of our program sample are shown in Figures 5 and 6, together with stars from the literature. Previous Li measurements and data selection for the plotting are summarized in the Appendix. Our sample efficiently covers lower metallicities than most previous samples, $[\text{Fe/H}] < -3.5$. The average of the Li abundances below $[\text{Fe/H}] = -3.5$ in our sample is $A(\text{Li}) = 1.90$, with a scatter of 0.10 dex, which does not represent a dispersion larger than can be accounted for by the errors of determination.

One possible concern for interpretation of our results is the different choice of temperature scale. Adopting temperatures 100 K higher makes the metallicities 0.08 dex higher and $A(\text{Li})$ 0.08 dex higher. A temperature scale ~300 K higher would bring the lithium abundances of our sample onto the Spite Plateau level. However, our analysis is carried out differentially to G64–12, for which our analysis of its Li abundance places it on the Spite Plateau. In addition, SDSS J1424+5615, at $[\text{Fe/H}] = -3.10$, was analysed by the same procedure and has an Li abundance close to the plateau value. Considering the Li abundances of G64–12 and SDSS J1424+5615, the overall temperature scale of our analysis is unlikely to be the reason for the low Li abundances among the stars with lower metallicity.

We conclude that all stars in our sample with $[\text{Fe/H}] < -3.5$ have lower Li abundance than the Spite Plateau, by ~0.3 dex, with no scatter within the measurement errors. Hereafter we combine our results with the literature sample.

As found from our sample, no star in the literature has comparable Li abundance to the Spite Plateau below...
### Table 6

| Object     | Species | $N$ | $\log \epsilon (X)$ | $\sigma$ | $[X/Fe]^a$ | $\sigma$ | $\alpha$ | $\delta$ | $\lambda$ |
|------------|---------|-----|----------------------|---------|------------|---------|---------|---------|---------|
| SDSS J1036-1212 | Na i     | 1   | 2.16                  | 0.10    | 0.30       | 0.15    | 0.25    | 0.15    | 0.15    |
| SDSS J1036-1212 | Ca ii    | 2   | 3.23                  | 0.13    | 0.40       | 0.13    | 0.40    | 0.13    | 0.40    |
| SDSS J1036-1212 | Fe ii    | 3   | 4.65                  | 0.12    | 0.40       | 0.12    | 0.40    | 0.12    | 0.40    |
| SDSS J1036-1212 | Sr ii    | 2   | 3.23                  | 0.13    | 0.40       | 0.13    | 0.40    | 0.13    | 0.40    |

Note. Abundances are determined differentially using G64–12 as a reference, and the uncertainties represent internal precision only.

$^a$ [X/Fe] is calculated using the solar abundance as Asplund et al. (2009).

### Table 6 (Continued)

| Object     | Species | $N$ | $\log \epsilon (X)$ | $\sigma$ | $[X/Fe]^a$ | $\sigma$ | $\alpha$ | $\delta$ | $\lambda$ |
|------------|---------|-----|----------------------|---------|------------|---------|---------|---------|---------|
| SDSS J1522+3055 | Li i     | 1   | 1.74                  | 0.11    | 0.30       | 0.11    | 0.30    | 0.11    | 0.30    |
| SDSS J1522+3055 | C (CH)   | 1   | 6.37                  | 0.10    | 0.30       | 0.10    | 0.30    | 0.10    | 0.30    |

[Fe/H] $\leq -3.5$, except for the primary of the double-lined binary system CS 22876–032. Thus, Li abundances appear to be uniformly low at extremely low metallicity. Our sample fills in the gap between Li measurements for stars around [Fe/H] $\sim -3.5$ and the two previously studied unevolved objects below [Fe/H] $< -4.0$, LAMOST J1253+0753
5.2. Chemical Inhomogeneity in the Early Universe

The early universe is expected to be chemically inhomogeneous, since a small number of nucleosynthesis events can create large abundance fluctuations from one place to another; the observed scatter of the elemental abundances for EMP stars can be used to quantify this inhomogeneity. The variations in yields from supernovae explosions of the first stars (Nomoto et al. 2013; Tominaga et al. 2014) are primarily determined by differences in their explosion energies and masses.

We have carried out $\chi^2$ tests to examine whether the observed scatter in $[X/Fe]$ ($A(Li)$ for Li) is significant. The probability that stars having the same abundance exhibit a scatter due only to measurement errors is listed in Table 7. Stars without detection are excluded from this analysis. We find statistically significant scatter for $[Na/Fe]$, $[Mg/Fe]$, $[Cr/Fe]$, $[Ti/Fe]$, $[Sr/Fe]$, and $[Ba/Fe]$. On the other hand, $A(Li)$, $[Ca/Fe]$, and $[Sc/Fe]$ do not exhibit significant scatter even at extremely low metallicity, although the number of stars with detection of $Sc$ is small. Thus, $Ca$ and $Fe$ seem to be produced at almost a constant ratio irrespective of the progenitor. This ensures the effectiveness of searches for metal-poor stars using $Ca$ lines. Since $C$ is detected in only three of our program stars, it is excluded from this discussion.

The significant scatter observed for many elements indicates that the natal clouds for early-generation stars are chemically inhomogeneous, reflecting variations in the yields of first stars and possible variations in mixing. However, the scatter in these elements is small compared to that predicted from the yields of supernovae explosions, considering the mass range of the progenitor (Kobayashi et al. 2006). The small scatter might indicate that the mini-halos hosting the early formation of EMP stars are also polluted by supernovae exploding in neighboring mini-halos (Jeon et al. 2017).

The abundance ratio $[Na/Fe]$ apparently exhibits a bimodal distribution (Figure 4). The Na abundances could be affected by both the adopted analysis technique and internal processes intrinsic to a given star. For instance, large NLTE effects in the formation of Na I D lines have been predicted (Andrievsky et al. 2007). However, the NLTE effect is almost systematic within the narrow parameter range of our sample. Indeed, no significant difference in stellar parameters is found between the stars with high and low Na abundances. This stands in clear contrast to previous studies of EMP stars, which often include red giants having a wide range of stellar parameters compared to main-sequence turnoff stars. Another difficulty in the studies

![Figure 4](image-url)
of red giants is that Na abundances could be affected by internal mixing during the evolution along the red giant branch. Therefore, it has been difficult to reach any conclusion about the scatter in Na abundance from the sample including red giants. Our study of turnoff stars provides a unique sample to investigate the scatter and bimodal distribution of Na abundance at the lowest metallicity. Hence, the bimodal distribution of Na Fe in our result is regarded not as a result of analysis, but as a physical property of EMP stars.

In order to assess the origin of the observed bimodality, we examine possible connections between the abundances of Na and those of other elements. First, the sample is divided into two groups at \([\text{Fe/H}] = 0.0\). We compute the probability that both subsamples have the same mean abundance, which is listed in the last column of Table 7. No significant difference is found for the abundances within the measurement errors. Even if the same test is made excluding SDSS J1424+5615, which has \(>0.4\) dex higher metallicity than rest of the stars, the results remain the same. Whereas correlation between [Na/Fe] and

![Figure 5.](image1.png)

**Figure 5.** \(A(\text{Li})\) as a function of [Fe/H]. Our sample is shown by red circles for the SDSS program stars and a star for G64–12. Literature data are shown as black squares, compiled from Bonifacio et al. (2007, 2012, 2015), Frebel et al. (2008), Aoki et al. (2009), Sbordone et al. (2010), Caffau et al. (2011), and Li et al. (2015). A double-lined spectroscopic binary system, CS 22876–032, is shown as open squares with the individual Li abundances connected to each other (Norris et al. 2000; González Hernández et al. 2008). The blue hatched region indicates the Spite Plateau, \(A(\text{Li}) = 2.2 \pm 0.1\).

![Figure 6.](image2.png)

**Figure 6.** \(A(\text{Li})\) as a function of \(T_{\text{eff}}\) and \(\log g\). The symbols are the same as in Figure 5.

| Element | Std. Deviation \(^a\) | \(P_{\text{scatter}}\) \(^b\) | \(P_{\text{Na-group}}\) \(^c\) |
|---------|----------------------|-----------------|-----------------|
| [Fe/H]  | 0.33                 | 0.00            | 0.14            |
| Li I    | 0.15                 | 0.21            | 0.07            |
| Na I    | 0.48                 | 0.00            | 0.00            |
| Mg I    | 0.30                 | 0.00            | 0.21            |
| Ca I    | 0.15                 | 0.16            | 0.19            |
| Cr I    | 0.26                 | 0.00            | ...             |
| Sc II   | 0.16                 | 0.06            | ...             |
| Ti II   | 0.26                 | 0.00            | 0.65            |
| Sr II   | 0.28                 | 0.00            | ...             |
| Ba II   | 0.79                 | 0.00            | ...             |

**Table 7.** Scatter in \([X/Fe]\) (or \(A(\text{Li})\) for Li) and Probabilities

**Notes.**

\(^a\) Stars without detection are excluded.
\(^b\) The probabilities that elemental abundances are the same for the whole sample (see text).
\(^c\) The probabilities of Na-rich and Na-poor groups having the same abundances.
A(Li) in globular clusters has been reported (Lind et al. 2009), we find no evidence for this in our sample.

Although the Na abundance may be related to a star’s C abundance, as discussed in Section 4.2.1, the difficulty in deriving C abundances for the majority of our EMP turnoff stars prohibits a clear conclusion. The [Na/Fe] bimodality and its association with C abundance has already been reported (e.g., Norris et al. 2013b). Note, however, that the difference in [Na/Fe] between their two populations (D~Na Fe 2.0 dex) is much larger than ours (D~Na Fe 0.8 dex). The apparent [Na/Fe] bimodality should be confirmed and investigated in detail by studies of a larger sample of EMP turnoff stars.

5.3. Metallicity Distribution Function

We now consider the metallicity distribution function (MDF) of the full sample of Aoki et al. (2013), shown in Figure 7. For the eight stars reanalyzed in the present study, we replace the metallicities with the newly derived ones. Since Aoki et al. (2013) adopt stellar parameters from the SSPP, which derives higher T\text{eff} than the present study, there is a difference in the metallicity scale between the two results. From a comparison of the stars in common between these studies (excepting SDSS J2309+2308 and SDSS J2005−1045), our metallicity scale is ~0.28 dex lower and the T\text{eff} scale is ~300 K lower than that of Aoki et al. (2013). Since metallicity is lowered by ~0.08 dex when a T\text{eff} 100 K lower is adopted, the 0.28 dex offset is almost consistent with the value expected from our T\text{eff} that is ~350 K cooler than the SSPP. We take a 0.28 dex shift into account in the replacement and generate the MDF on the scale of the present study. The optimal bin size is determined following Shimazaki & Shinomoto (2007) as 0.10 dex. We also create generalized histograms with a Gaussian function whose \( \sigma \) is 0.10 dex. No significant spurious features are seen in the distribution. Note that our MDF above [Fe/H] ~ −3.4 appears to be significantly affected by the incompleteness of the target selection (Aoki et al. 2012).

Schörck et al. (2009) and Li et al. (2010) reported a cutoff in the MDFs for giants and turnoff stars among candidate metal-poor stars from the Hamburg/ESO survey (Christlieb et al. 2008), at around [Fe/H] ~ −3.5. We do not find evidence for such a cutoff in the MDF of our sample down to [Fe/H] ~ −4.0, consistent with Yong et al. (2013). If the metallicity correction of 0.28 dexis not applied, the existence of the tail is still clear.

5.4. Extremely Metal-poor CEMP-s Stars

SDSS J1036+1212 is one of the lowest-metallicity CEMP-s stars known. Although Behara et al. (2010) reported on a detailed abundance pattern for SDSS J1036+1212, we could not detect as many elements as they reported. We obtained the VLT/UVES spectrum of SDSS J1036+1212 used by Behara et al. (2010) for their abundance analysis from the ESO archive. However, we could not reproduce their reported detection of Eu. Hence, we discuss this object here based solely on the abundance results obtained by the present work.
SDSS J2309+2308 exhibits an excess of Ba, and is another candidate CEMP-s star, although only a weak upper limit on its C abundance is determined by our study.

CEMP-s stars are generally considered to have experienced mass transfer from a companion on the asymptotic giant branch in which large amounts of C and s-process elements, including Ba, are synthesized. The reported high frequency of binaries among such stars supports this scenario (Starkenburg et al. 2014; Hansen et al. 2016). Although neither of these two stars exhibited a variation in radial velocity between our observations and Aoki et al. (2013), the radial velocity of SDSS J1036+1212 in our work is ~14 km s⁻¹ larger than in Behara et al. (2010), suggesting the likely binarity of this object.

Although two EMP CEMP-s candidates are found in our sample, there is a lack of such stars among the red giants as shown in Figure 8. Among the CEMP-s stars with [Fe/H] < −3.0, almost all stars with [Ba/Fe] > +1.0 are main-sequence stars. The lack of CEMP-s red giants in [Fe/H] < −3.0 may be related to the first dredge-up that occurs at the beginning of the red giant phase. First dredge-up dilutes the surface material of a star to the inner regions. If the over abundance of Ba is provided by mass transfer from a companion star to the stellar surface, first dredge-up significantly reduces the surface Ba abundance. Such dilution is effective only when (i) the transferred mass is small compared to the dredged-up mass, and (ii) transferred material is not mixed with the interior during the main-sequence stage. Since the dredged-up mass is large (~50% of the stellar mass), the first condition is generally satisfied (see also Masseron et al. 2012). Therefore, the existence of EMP CEMP-s turnoff stars is a potential constraint on the efficiency of mixing processes during the main-sequence phase, such as thermohaline mixing (Stancliffe et al. 2007). The reason for the lack of CEMP-s red giants at extremely low metallicity might be that the efficiency of the operation of the s-process is low in this regime.

Note that the above discussion using the SAGA database can be affected by sample selection, since some past studies focus on red giants while others focus on turnoff stars. For example, Jacobson et al. (2015) have constructed a sample of metal-poor stars on the red giant branch using photometric estimates of metallicity, and reported a lack of extremely carbon-rich objects. Jacobson et al. (2015) suspected that the use of photometric selection of metal-poor stars may have resulted in a bias against such objects. On the other hand, some previous studies focused on turnoff CEMP stars (e.g., Aoki et al. 2008).

To obtain a clear conclusion regarding the lack of CEMP-s red giants at [Fe/H] < −3, we require a larger sample of EMP stars including both red giants and turnoff stars.

### 6. Summary

We analyze eight unevolved EMP stars for which Aoki et al. (2013) have previously estimated abundances from snapshot spectroscopy. Based on newly obtained high-resolution, high-S/N spectra, we first compare different methods to derive stellar parameters. Analysis of Balmer-line profiles yields estimates of $T_{\text{eff}}$ consistent with an analysis of Fe lines and with estimates based on $V - K_s$ color. The estimates of surface gravity obtained from the Balmer-line analysis are also consistent with those from the analysis of Fe lines and from Gaia parallaxes. In contrast, the SSPP procedure results in higher $T_{\text{eff}}$ estimates than the Balmer-line analysis for EMP stars.

We carry out a differential abundance analysis, with G64−12 as a reference, adopting the parameters obtained by Balmer-line analysis. The use of the reference star should cancel out NLTE/3D effects and uncertainties in atomic data. We obtain the following results:

1. Seven of the eight stars have [Fe/H] < −3.5 and all have $T_{\text{eff}} > 5500$ K.
2. Lithium abundances of all seven stars below [Fe/H] = −3.5 are lower than the Spite Plateau, without significant scatter. This result could provide a constraint on proposed Li-depletion mechanisms.
3. We found significant scatter in [Na/Fe], [Mg/Fe], [Cr/Fe], [Ti/Fe], [Sr/Fe], and [Ba/Fe]. On the other hand, the scatter in [M/Fe], [Sc/Fe], and [Ca/Fe] is not significant. The observed bimodality in [Na/Fe], with a separation of 0.8 dex, requires explanation; further confirmation and detailed investigation with larger samples is desired.
4. We confirm the most metal-poor CEMP-s star yet known and identify another CEMP-s candidate with [Fe/H] < −4.0. From literature data, a lack of CEMP-s red giants with [Fe/H] < −3.0 is seen. Their absence may be due to the combined effect of metallicity dependence of s-process efficiency and dilution caused by first dredge-up.
From the point of the comparison between observations and suggested Li-depletion models, atomic diffusion with turbulent mixing (e.g., Richard et al. 2005) should be investigated for a wider range of parameter space, especially toward lower metallicity. More quantitative evaluation is needed for other models, such as Li depletion due to astration by first stars or Li depletion in the pre-main-sequence phase. More precise stellar parameters, in particular evolutional phase and mass, and more precise abundances are clearly desired. Improved \( \log g \) estimates that will be provided by \textit{Gaia} parallaxes should result in significant progress. It is also desired to increase the sample size of EMP main-sequence turnoff stars.

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Appendix

\textbf{Adopted Values in the Tables}

Previous measurements of Li abundances for metal-poor stars are listed in Table 8. We exclude stars with \( T_{\text{eff}} < 5500 \) K or \([\text{Fe/H}] > -2.5\). There are overlaps in the samples among Aoki et al. (2009), Sbordone et al. (2010), and Bonifacio et al. (2007), for which we gave priority in that order. Each star appears once in each figure, though we plot both our results and the results of Aoki et al. (2009) for G64–12.

\begin{table}[h]
\centering
\caption{Li Abundance Measurements from Previous Studies and in this Work}
\begin{tabular}{|l|l|l|l|l|}
\hline
Object & \( T_{\text{eff}} \) & \( \log g \) & [Fe/H] & \( \Delta(\text{Li}) \) & Reference \\
\hline
CD –24°17504 & 6180 & 4.4 & –3.40 & 2.08 & Aoki et al. (2009) \\
BS 16023–046 & 6324 & 4.30 & –2.97 & 2.14 & Sbordone et al. (2010) \\
BS 1645–095 & 4574 & 4.50 & –2.97 & 2.18 & Bonifacio et al. (2007) \\
BS 1696–061 & 6035 & 3.75 & –3.05 & 2.12 & Bonifacio et al. (2007) \\
BS 1750–063 & 6078 & 4.50 & –3.05 & 1.93 & Sbordone et al. (2010) \\
BS 17572–100 & 6242 & 4.75 & –2.92 & 2.05 & Bonifacio et al. (2007) \\
CS 22177–009 & 6371 & 4.00 & –2.75 & 2.15 & Sbordone et al. (2010) \\
CS 22188–031 & 6177 & 4.30 & –3.17 & 2.15 & Sbordone et al. (2010) \\
CS 22876–020 & 6129 & 4.40 & –3.03 & 1.57 & Sbordone et al. (2010) \\
CS 22876–021 & 6500 & 4.0 & –3.66 & 2.22 & González Hernández et al. (2008) \\
CS 22888–031 & 5900 & 4.6 & –3.57 & 1.75 & González Hernández et al. (2008) \\
CS 22948–093 & 5925 & 4.50 & –3.47 & 1.84 & Sbordone et al. (2010) \\
CS 22950–173 & 6151 & 5.00 & –3.30 & 2.01 & Bonifacio et al. (2007) \\
CS 22953–037 & 6380 & 4.4 & –3.43 & 1.96 & Aoki et al. (2009) \\
CS 22965–054 & 6356 & 4.25 & –3.30 & 1.94 & Bonifacio et al. (2007) \\
CS 22966–011 & 6365 & 4.25 & –3.31 & 1.93 & Sbordone et al. (2010) \\
CS 29499–084 & 6335 & 4.20 & –2.78 & 2.19 & Sbordone et al. (2010) \\
CS 29499–060 & 6325 & 4.25 & –2.91 & 2.15 & Sbordone et al. (2010) \\
CS 29506–090 & 6364 & 4.25 & –2.89 & 2.16 & Bonifacio et al. (2007) \\
CS 29514–007 & 6310 & 3.9 & –2.84 & 2.16 & Aoki et al. (2009) \\
CS 29516–028 & 6089 & 3.75 & –3.04 & 2.03 & Bonifacio et al. (2007) \\
CS 29518–020 & 6245 & 4.00 & –2.90 & 2.161 & Sbordone et al. (2010) \\
CS 29518–043 & 6304 & 4.40 & –3.22 & 1.788 & Sbordone et al. (2010) \\
CS 29519–093 & 6204 & 4.75 & –3.04 & 2.080 & Sbordone et al. (2010) \\
CS 29519–043 & 6318 & 4.00 & –2.70 & 2.18 & Bonifacio et al. (2007) \\
CS 29519–043 & 6349 & 4.10 & –2.66 & 2.201 & Sbordone et al. (2010) \\
CS 29506–007 & 6285 & 4.10 & –2.88 & 2.14 & Sbordone et al. (2010) \\
CS 29506–090 & 6273 & 4.00 & –2.91 & 2.15 & Bonifacio et al. (2007) \\
CS 29506–090 & 6287 & 4.20 & –2.83 & 2.102 & Sbordone et al. (2010) \\
CS 29506–090 & 6303 & 4.25 & –2.83 & 2.12 & Bonifacio et al. (2007) \\
CS 29514–007 & 6281 & 4.10 & –2.80 & 2.21 & Sbordone et al. (2010) \\
CS 29516–028 & 5839 & 4.40 & –3.52 & 1.904 & Sbordone et al. (2010) \\
CS 29518–020 & 6127 & 4.30 & –2.86 & 2.052 & Sbordone et al. (2010) \\
CS 29518–043 & 6242 & 4.50 & –2.77 & 2.14 & Bonifacio et al. (2007) \\
CS 29518–043 & 6376 & 4.25 & –3.25 & 2.121 & Sbordone et al. (2010) \\
CS 29518–043 & 6432 & 4.25 & –3.20 & 2.17 & Bonifacio et al. (2007) \\
\hline
\end{tabular}
\end{table}
Table 8  
(Continued)

| Object       | $T_{	ext{eff}}$ | log $g$  | [Fe/H]  | A(Li)   | Reference            |
|--------------|-----------------|----------|----------|---------|----------------------|
| CS 2927−015  | 6276            | 4.00     | −3.53    | 2.091   | Sbordone et al. (2010) |
|              | 6242            | 4.00     | −3.55    | 2.07    | Bonifacio et al. (2007) |
| CS 3030−024  | 6375            | 4.00     | −2.71    | 2.143   | Sbordone et al. (2010) |
|              | 6334            | 4.00     | −2.75    | 2.12    | Bonifacio et al. (2007) |
| CS 3032−145  | 6403            | 4.30     | −3.02    | 2.086   | Sbordone et al. (2010) |
|              | 6253            | 4.00     | −3.09    | 2.125   | Sbordone et al. (2010) |
|              | 6242            | 4.00     | −3.08    | 2.13    | Bonifacio et al. (2007) |
| CS 3034−070  | 6302            | 4.10     | −3.02    | 2.064   | Sbordone et al. (2010) |
| CS 31061−032 | 6369            | 4.25     | −2.62    | 2.221   | Sbordone et al. (2010) |
|              | 6409            | 4.25     | −2.58    | 2.25    | Bonifacio et al. (2007) |
| G64−12       | 6270            | 4.4      | −3.37    | 2.18    | Aoki et al. (2009)    |
| G64−12       | 6285            | 4.30     | −3.38    | 2.22    | This work            |
| G64−37       | 6290            | 4.4      | −3.23    | 2.04    | Aoki et al. (2009)    |
| HE 0148−2611 | 6400            | 4.10     | −3.18    | 2.000   | Sbordone et al. (2010) |
| HE 0233−0343 | 6100            | 3.4      | −4.7     | 1.77    | Hansen et al. (2014)  |
| HE 1148−0037 | 5990            | 3.7      | −3.46    | 1.90    | Aoki et al. (2009)    |
| HE 1327−2326 | 6180            | 3.7      | −5.71    | <0.70   | Frebel et al. (2008)  |
| HE 1413−1954 | 6302            | 3.80     | −3.50    | 2.035   | Sbordone et al. (2010) |
| LAMOST J1253+0753 | 6030 |
| LP 815−43   | 6453            | 3.80     | −2.88    | 2.229   | Sbordone et al. (2010) |
| SDSS J002113−005005 | 6546 |
| SDSS J002749+140418 | 6125 |
| SDSS J0040−16 | 6360            | 4.4      | −3.29    | 1.99    | Aoki et al. (2009)    |
| SDSS J0120−1001 | 5627            | <3.70    | −3.84    | 1.97    | This work            |
| SDSS J0212+0137 | 6333            | 4.0      | −3.59    | 2.04    | Bonifacio et al. (2015) |
| SDSS J031745+002304 | 5786 |
| SDSS J082118+181931 | 6158 |
| SDSS J082521+040334 | 6340 |
| SDSS J090733+024608 | 5934 |
| SDSS J102915+172927 | 5811 |
| SDSS J1033+40 | 6370            | 4.4      | −3.24    | 2.09    | Aoki et al. (2009)    |
| SDSS J1035+0641 | 6262            | 4.0      | <−5.07   | <1.1    | Bonifacio et al. (2015) |
| SDSS J1036+1212 | 5502            | 3.74     | −3.62    | 1.97    | This work            |
| SDSS J113528+010848 | 6132 |
| SDSS J1137+2553 | 6310            | 3.2      | −3.03    | 1.99    | Bonifacio et al. (2012) |
| SDSS J122935+262445 | 6452 |
| SDSS J130017+263238 | 6593 |
| SDSS J1424−5615 | 6107            | 4.20     | −3.65    | 2.10    | Bonifacio et al. (2012) |
| SDSS J143632−091831 | 6340 |
| SDSS J144640+124917 | 6189 |
| SDSS J1522+3055 | 5505            | 3.75     | −3.16    | 1.62    | Bonifacio et al. (2012) |
| SDSS J154246+054426 | 6179 |
| SDSS J1640+3709 | 6211            | 4.42     | −3.48    | 1.97    | Bonifacio et al. (2012) |
| SDSS J1742+2531 | 6345            | 4.00     | −3.48    | 1.97    | Bonifacio et al. (2012) |
| SDSS J2005+1045 | 6263            | 3.98     | −3.86    | <1.8    | Bonifacio et al. (2015) |
| SDSS J223143−094834 | 6053 |
| SDSS J230814+085526 | 6015 |
| SDSS J2309+2308 | 5875            | 3.82     | −3.01    | <1.39   | Bonifacio et al. (2012) |
| SDSS J233113−010933 | 6246 |
| SDSS J2349−3832 | 5972            | 4.47     | −3.08    | 2.22    | Bonifacio et al. (2012) |

Note. The first reference for each star in this table is adopted in the plots (Figures 5 and 6).

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