The Lithium Abundances from the Large Sky Area Multi-object Fiber Spectroscopic Telescope Medium-resolution Survey. I. The Method

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Abstract

One of the purposes of taking spectra for millions of stars through the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) medium-resolution survey (MRS) is to obtain the elemental abundances, so that one can trace the origin and evolution for the element of interests. Lithium is one of such elements of great importance, which exhibits many puzzling behaviors. Investigating the lithium abundances to a uniquely large sample of stars is essential to understand its origin and evolution. In this paper, we present the lithium abundances obtained from the LAMOST MRS spectra calculated by the template-matching method. Our data set consists of 294,857 spectra that corresponds to 165,479 stars with a resolution power of $\Delta\lambda/\lambda \sim 7500$. We compared the lithium abundances derived from our work with those using the high-resolution spectra and found a good consistence. The errors of lithium abundances are discussed. Our results suggest that the distribution of lithium abundances show two clear peaks at $+2.6$ and $+1.0$ dex, respectively. This sample is potentially important for investigating physical mechanisms occurring inside stars that alter the surface lithium abundance.

Unified Astronomy Thesaurus concepts: Stellar abundances (1577); Stellar evolution (1599); Chemically peculiar stars (226)

Supporting material: machine-readable table

1. Introduction

Lithium is one of the most interesting elements, and shows complex pattern in different types of stars, which are not well understood.

The primordial lithium was synthesized during the first 20 minutes of the universe. Based on the baryon density inferred from the cosmic microwave background observations or from the primordial deuterium measurements, the standard big bang nucleosynthesis predicts that the primordial lithium abundance is $\sim 2.7$ dex (Cyburt et al. 2003; Spelger et al. 2003; Cyburt et al. 2008, 2016; Coc et al. 2012, 2014; Fields et al. 2020), which is a significant discrepancy with the observed value. Spite & Spite (1982) and the following works (Bonifacio & Molaro 1997; Asplund et al. 2006; Bonifacio et al. 2007; Shi et al. 2007; Molaro 2008; Lind et al. 2009; Sbordone et al. 2010) confirmed that most of the warm (>5700 K) metal-poor ($-2.4 < [\text{Fe}/\text{H}] < -1.4$) main-sequence (MS) stars display a plateau of the Li abundance (the so-called plateau), sharing a similar value at $A(\text{Li}) \sim 2.2$ dex. This discrepancy is generally denominated as the cosmological lithium problem. Many studies have been devoted to solve this problem (Cov et al. 2012; Kajino et al. 2012; Olive et al. 2012; Kusakabe & Kawasaki 2015; Hou et al. 2017; Kang et al. 2019; Korn 2020; Sasankan et al. 2020); however, it is still unsolved (see a recent review, Mathews et al. 2020).

For the Milky Way disk, the increase in measurements provided by recent works have indicated that there is a different behavior in lithium evolution between the thin and thick disk stars. At the lower metallicity end, they present the same lithium abundances, while, the increase in lithium abundances is steeper in thin disks than in thick disks at higher metallicities (Molaro et al. 1997; Guiglion et al. 2016; Fu et al. 2018). The behavior of lithium abundances in the thick disk as a function of metallicity is still in debate.

Also, it is found that, for the disk stars, the upper envelope of lithium abundances increase above the spike plateau level at higher metallicities (Ramírez et al. 2012; Delgado Mena et al. 2015; Guiglion et al. 2016; Fu et al. 2018), which indicates that the Galaxy has undergone a history of lithium enrichment since the big bang. However, the sources of enrichment are not well understood, which is referred as the Galactic lithium problem. Several sources have been proposed: (a) the spallation of ISM atoms by high-energy cosmic rays, which accounts for less than 30% of the meteorite lithium abundance (Reeves et al. 1970; Meneguzzi et al. 1971; Lemoine et al. 1998; Romano et al. 2001; Prantzos 2012); (b) the neutrino process in the core-collapse supernovae, although no lithium lines have been found from the supernovae’s spectra (Domogatskii et al. 1978; Hartmann et al. 1999; Yoshida & Kajino 2005; Yoshida et al. 2004); (c) classical novae explosions during which $^7\text{Li}$ (Izzo et al. 2015) or $^7\text{Be}$ lines (will decay to $^7\text{Li}$ in a short time) have been detected (Tajitsu et al. 2015, 2016; Molaro et al. 2016; Selvelli et al. 2018); and (d) the evolved stars, which are at the red giant branch, the red clump, or the asymptotic giant branch phases. It is found that some evolved stars (e.g., Smith & Lambert 1989, 1990; Abia et al. 1999; Yan et al. 2018; Casey et al. 2019; Gao et al. 2019; Singh et al. 2019; Kumar et al. 2020; Yan et al. 2021, and references therein) have lithium abundances even higher than the meteoritic value.

Above the solar metallicities ([Fe/H] > 0), lithium abundances in solar neighborhood stars show a puzzling decrease...
(Delgado Menà et al. 2015; Guiglion et al. 2016; Bensby & Lind 2018; Buder et al. 2018; Fu et al. 2018). A similar situation has been found for the dwarfs and subgiants in Galactic bulge (Bensby et al. 2020). Stonkutë et al. (2020) presented that, at the supersolar-metallicities, the lithium abundances descended by 0.7 dex in the $\text{[Fe/H]}$ range from $+0.10$ to $+0.55$ dex. However, Randich et al. (2020) noted that their solar- and supersolar-metallicity stars all have higher lithium values with a peak at $\sim +3.4$ dex for the two most metal-rich open clusters; thus, they suggested that the previous findings based on field stars were biased by selection effects.

The depletion of lithium on the surface of a star makes the studies of the phenomenon on the lithium abundances more complicated. Lithium will be destroyed at relatively low temperatures in stellar interiors (Deliyannis et al. 2019), and the lithium destruction can be observed at the photosphere if standard convective mixing reaches down as far as the lithium-burning regions. In pre-MS and MS stars, considerable evidence suggests that the dominant mechanism depleting surface lithium over time is the rotational induced mixing (Deliyannis et al. 1994, 1998; Boesgaard et al. 1998, 2005, 2016, 2020; Cummings et al. 2017). While in subgiant and giant stars the surface lithium may be consumed more severely due to the deepening of the convective zone, rotational mixing and/or thermohaline mixing (Anthony-Twarog et al. 2018, Anthony-Twarog 2021, Deliyannis et al. 1990; Ryan & Deliyannis 1995; Charbonnel & Talon 1999; Charbonnel & Lagarde 2010).

In order to reveal the lithium behaviors, a large and homogeneous sample with precise lithium abundances is needed. Such efforts have been attempted in recent spectroscopic surveys, such as the Gaia-ESO survey (e.g., Fu et al. 2018; Randich et al. 2020), the Archéologie avec Matisse Basée sur les aRchives de l’ESO (AMBRE) project (e.g., Guiglion et al. 2016; Prantzos et al. 2017), Galactic Archaeology with HERMES (GALAH) survey (e.g., Žerjal et al. 2019; Deepak & Reddy 2020; Gao et al. 2020), etc. The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; Cui et al. 2012; Zhao et al. 2012) launched the medium-resolution ($\Delta \lambda/\lambda \approx 7500$) spectroscopic survey (hereafter MRS; Liu et al. 2020) in September 2018. Its data are potentially important for lithium abundance investigation in the sense that it has already obtained massive high-quality MRS spectra that cover lithium resonance line in the red band.

The purpose of this paper is to present the derived lithium abundances for 294,857 spectra of 165,479 targets from the LAMOST MRS spectra. Our paper is organized as follows: Section 2 describes the spectra and stellar parameters we used, and Section 3 presents the method we developed for deriving lithium abundances. Validation of the method and error estimation are provided in Section 4 and Section 5, respectively. The resulting catalog and the distributions of the lithium abundances are shown in Section 6. Finally, a brief summary is given in Section 7.

2. Data

2.1. Spectra

The LAMOST MRS spectra consist of the blue and red band, and the wavelength ranges are $4950 \sim 5350$ and $6300 \sim 6800$ Å, respectively (Liu et al. 2020). In our study, the red-band spectra observed from September 2017 to June 2019 with a signal-to-noise ratio (S/N) higher than 10 have been selected.\(^5\)

2.2. Stellar Parameters

The effective temperature ($T_{\text{eff}}$), surface gravities ($\log g$), metallicities ($\text{[Fe/H]}$), and microturbulent velocities ($\xi$) of our sample stars have not been well determined from the MRS spectra at the moment; thus, we adopted the stellar parameters from the following works:

— The stellar parameters of LAMOST DR7: They were derived from the LAMOST low-resolution spectra with the LAMOST Stellar Parameter Pipeline (LASP; Luo et al. 2015) using a template-matching method, and the template spectra are produced based on the ELODIE spectra library (Prugniel & Soubiran 2001; Prugniel et al. 2007). This parameter data set covers 267,962 spectra of 150,553 stars in our sample (hereafter the LASP-SP).

— The stellar parameters of SDSS DR16: They were from the Apache Point Observatory Galactic Evolution Experiment (APOGEE)-2/Sloan Digital Sky Survey (SDSS-IV survey, Jónsson et al. 2020 determined by the APOGEE Stellar Parameter and Chemical Abundances Pipeline ASPCAP, García Pérez et al. 2016). This method matches the observed spectra to the precomputed theoretical templates calculated with a local thermodynamic equilibrium (LTE) assumption. This parameter data set covers 26,895 spectra of 14,926 stars in our sample (hereafter the APOGEE-SP).

For the stars have both the LASP and APOGEE parameter, the latter is adopted, as APOGEE is a high-resolution survey.

Finally, our sample consists of 294,857 spectra of 165,479 targets, spanning a range of stellar atmospheric parameters: $3500 \text{ K} < T_{\text{eff}} < 7000 \text{ K}$, $0.1 \text{ dex} < \log g < 5.0 \text{ dex}$, $-2.5 \text{ dex} < \text{[Fe/H]} < +0.5 \text{ dex}$. Figure 1 presents the stellar parameter spaces of our sample in the planes of $T_{\text{eff}}$, log $g$ (a), $T_{\text{eff}}$, [Fe/H] (b), and [Fe/H], log $g$ (c).

The microturbulent velocity is important when derived the lithium abundance, especially for the strong lines; thus, empirical relations have been adopted to determine this parameter. For giants ($\log g \leq 3.5 \text{ dex}$) with [Fe/H] higher than $-1.0 \text{ dex}$, the relation from Hollzman et al. (2018) is adopted, which was derived based on a metal-rich giant subsample of the APOGEE Data Releases 13:

$$
\xi = 10^{(0.226 - 0.0228 \log g + 0.0297(\log g)^2 - 0.0113(\log g)^3)}, \tag{1}
$$

where the unit $\xi$ is in kilometers per second. While a linear relationship from García Pérez et al. (2016) is used for metal-poor ([Fe/H] $\leq -1.0$ dex) giants:

$$
\xi = 2.478 - 0.325 \log g. \tag{2}
$$

For hot dwarfs ($T_{\text{eff}} > 5000 \text{ K}$, log $g > 3.5 \text{ dex}$), we follow Gao et al. (2018)’s suggestion, which has also been adopted for the GALAH survey (Buder et al. 2021):

$$
\xi = 1.1 + 10^{-4}(T_{\text{eff}} - 5500 \text{ K})
+ 4 \times 10^{-7}(T_{\text{eff}} - 5500 \text{ K})^2, \tag{3}
$$

while a constant microturbulence of $1.0 \text{ km s}^{-1}$ is set for dwarfs with $T_{\text{eff}}$ lower than $5000 \text{ K}$.\(^5\)
3. Method

The approach employed in this study is a revised method we used earlier to search for lithium-rich giants from the LAMOST low-resolution spectra (Gao et al. 2019). The method is based on template matching, and we briefly describe the processes as follows.

3.1. The Synthetic Spectra

The synthetic spectra have been calculated using the SPECTRUM synthesis code (v2.77, 2017, Gray 1999) based on the ATLAS9 stellar atmosphere model from Castelli & Kurucz (2003) under an LTE assumption, and the atomic line data for lithium are from Shi et al. (2007). The resolution was...
The grids of stellar parameters and lithium abundance of synthetic spectra were set as $3500 \text{ K} < T_{\text{eff}} < 6500 \text{ K}$ in a step of 100 K, $4500 \text{ K} < T_{\text{eff}} < 6500 \text{ K}$ in a step of 200 K, and $T_{\text{eff}}\geq 6500 \text{ K}$. The microturbulent velocities were calculated by the empirical relations presented in Section 2.

**Figure 3.** Three cases of comparison between the synthetic spectra (black solid lines) and the interpolated ones (red dashed lines). The light blue region indicates the position of the Li I resonance line. The stellar parameters are shown in the sequence of $T_{\text{eff}}$, log $g$, [Fe/H], and [Li/Fe], and the residuals are presented in the bottom of each panel.

**Figure 4.** Four matching examples. The black dotted lines and the red solid lines are the observed and the best-matching synthetic spectra, respectively. The wavelength range of 6706–6709 Å to compute $\chi^2$ is marked as light blue region. The stellar parameters ($T_{\text{eff}}$, log $g$, [Fe/H]), and A(Li) are presented, and the residuals are plotted in the bottom of each panel.

fixed as 0.5 Å for all of the synthetic spectra with the microturbulent velocities calculated by the empirical relations presented in Section 2.

The grids of stellar parameters and lithium abundance of synthetic spectra were set as $3500 \text{ K} \leq T_{\text{eff}} \leq 4500 \text{ K}$ in a step of 200 K, $4500 \text{ K} < T_{\text{eff}} \leq 6500 \text{ K}$ in a step of 100 K,
**Figure 5.** Distribution of the atmospheric parameters for the common sources. The blue dots and orange squares indicate the GALAH and GES targets, respectively.

**Figure 6.** Comparisons of the lithium abundances calculated by our method ($A(\text{Li})_{\text{LAMOST}}$) and those determined from GALAH ($A(\text{Li})_{\text{GALAH}}$) (a) and GES ($A(\text{Li})_{\text{GES}}$) (b). The black solid lines are the one-to-one correspondence, while the black dashed lines are the overall shifts. The distribution of the differences between $A(\text{Li})_{\text{LAMOST}}$ and $A(\text{Li})_{\text{GALAH,GES}}$ with the Gaussian fitting result is plotted in the top of each panel, and the number of targets ($N$), the mean value ($\mu$), the uncertainty of the mean ($\sigma_\mu$), and the dispersion ($\sigma$) are presented. The meanings of the symbols are the same as in Figure 5.
6500 K \leq T_{\text{eff}} \leq 7500 K \text{ in a step of 200 K, } 0.0 \leq \log g \leq 5.0 \text{ in a step of 0.5 dex, } 
-2.6 \leq [\text{Fe}/\text{H}] \leq 0.6 \text{ in a step of 0.2 dex, and } 
-3.0 \leq [\text{Li}/\text{Fe}] \leq 5.1 \text{ in a step of 0.1 dex. For the}

synthetic spectra with [Fe/H] < -0.6, we enhanced the abundances of \(\alpha\)-elements by 0.4 dex.

The synthetic spectra around the \(\text{Li}\) resonance line at 6708 Å with four sets of stellar parameters are shown in Figure 2.

### 3.2. The Lithium Abundances

The lithium abundances were estimated with a template-matching method, and the following steps have been used:

1. Preprocessing: Two initial procedures had to be done. First, we corrected the wavelength of an observed spectrum to the rest-frame scale using the radial velocity derived by cross correlation. Second, we degraded the resolution of the synthetic spectra according to the observed ones.

2. Generating: We generated a set of synthetic spectra by interpolating the adjacent grids of the synthetic spectra for the stellar atmospheric parameters of a target star, [Li/Fe] of the generating spectra were varying from −3.0 to +5.1. In order to examine the impact of the uncertainty introduced by our interpolation algorithm on the determination of lithium abundances, we compared the synthetic spectra with the interpolated ones for the same stellar parameters and lithium abundances for three cases as shown in Figure 3. It was found that the differences were less than 1%, which had little effects on our results.
The differences in $A(Li)$ between two epoch observations as a function of $S/N$. The red dots and the vertical error bars represent the mean and the standard deviation, respectively. The bin size is 50.

| Table 1 |
|---------|
| Coefficients of the Polynomials (5)–(8) |

| $a_0$       | $a_1$       | $b_0$       | $b_1$       | $b_2$       | $b_3$       |
|------------|------------|------------|------------|------------|------------|
| 2.09(-1)   | -2.44(-1)  | 5.14       | -2.58(-2)  | 4.33(-7)   | -2.39(-11) |
| $c_0$      | $c_1$      | $c_2$      | $c_3$      |
| 6.80(-2)   | -8.54(-4)  | -1.01(-2)  | 2.18(-3)   |
| $d_0$      | $d_1$      | -1.00(-1)  | 5.13(-2)   |

Note: The integers in parentheses refer to powers of 10; for example, 2.09(-1) represents $2.09 \times 10^{-1}$.

3. Calculating: We computed a chi-square ($\chi^2$) between the observed and each synthetic spectra around the wavelength range of 6706–6709 Å, which covered the Li i resonance line. The $\chi^2$ is defined as

$$\chi^2 = \sum_{i=1}^{N} \frac{(O_i - S_i)^2}{\sigma_i^2},$$  \hspace{1cm} (4)

where $O_i$ and $S_i$ are the flux of the $i$th point of observed and synthetic spectra, respectively, $\sigma_i$ is the error of the $i$th observed flux, and $N$ is the number of points used in calculation. Before calculating $\chi^2$, it was necessary to adjust the continuum of the synthetic and observed spectra to the same level. We calculate the flux ratio between the observed and synthetic spectra in the wavelength range of 6675–6740 Å (the Li i resonance line has been masked) and fit this set of ratio with a second-order polynomial. Finally, the continuum of a synthetic spectrum is adjusted to the level of the observed one by multiplying the fit values.

4. Estimating: We fitted the $\chi^2$ array with a third-order polynomial to determine the minimum $\chi^2$, and the $[Li/Fe]$ can be determined. Then we transformed $[Li/Fe]$ into the commonly used form $A(Li)^6$: $A(Li) = [Li/Fe] + [Fe/H] + A(Li)_0$, here $A(Li)_0$ was adopted as 1.15 dex according to the value used in SPECTRUM code.

Figure 4 shows four matching examples: the black dotted lines and red solid lines are the observed and the best-matched synthetic spectra, respectively. The residuals plotted at the bottom of each panel indicate that the deviations in the considered region between the observed and the best-matched spectrum are less than 1%.

4. Validation of the Method

It is necessary to validate our method used for calculating the lithium abundances; therefore, we compared $A(Li)$ derived by us with those from the high-resolution spectral analysis for the common stars in GALAH DR3 (Buder et al. 2021, GALAH hereafter) and Gaia-ESO Survey iDR4 (the fourth internal data release of the Gaia-ESO Survey; the catalog is available on the ESO Phase 3 webpage7, GES hereafter). There are 3499 targets in GALAH (for flag$_{[Li/Fe]} = 0$) and 49 in GES have also been observed by LAMOST MRS, respectively. The distribution of stellar parameters of these targets is shown in Figure 5.

To avoid the difference caused by adopting different stellar parameters in each sample, we adopted $T_{eff}$, $\log g$, and $[Fe/H]$ from GALAH and GES in our calculation, and the comparisons of $A(Li)$ estimated by our method with these from GALAH and GES are presented in Figure 6. We found a good agreement with an offset of $+0.09$ dex and a scatter of $0.12$ dex for the GALAH common stars (panel (a)). The uncertainty of this offset is $0.02$ dex, which indicates that $+0.09$ dex is a statistically significant offset. It needs to be pointed out that the lithium abundances provided by GALAH are based on non-LTE, while GES and ours are based on an LTE assumption. Amarsi et al. (2020) presented that the non-LTE effects for the Li i resonance lines are negative with a typical value of $\Delta A(Li)_{\text{non-LTE}} = -0.10$ dex for dwarf stars. The majority of the common GALAH samples are dwarfs; therefore, the offset can be explained by the non-LTE effects. The comparison with GES shows an offset of $+0.03$ dex with a scatter of $0.17$ dex (panel (b)). The uncertainty of this offset is $0.02$ dex. We also investigate the differences in $A(Li)$ as functions of each stellar parameter and find that there is no obvious correlation for any parameter, as shown in Figure 7.

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6. $A(Li) = \log(N_{Li}/N_{H}) + 12$, where $N_{Li}$ and $N_{H}$ is the number density of lithium and hydrogen, respectively.
7. http://www.eso.org/qi/
5. Error Estimation

The quality of the observed spectra and the uncertainties in stellar parameters will influence the accuracy of lithium abundance measurement, and we discuss the errors caused by these factors as follows.

5.1. Errors Due to the Quality of Spectra

Taking advantage of the repeated observations for the same stars, we estimate the errors of lithium abundances related to the quality of spectra. To do this, 43,033 targets having repeated observations with the differences in spectral S/N less than 20% have been selected. Figure 8 shows the difference in A(Li) between two observed spectra of a target as a function of S/N. The results indicate that the differences in A(Li) measured from the spectra are sensitive to their S/Ns, which is reasonable. We note that the dispersions decrease from 0.3–0.1 dex with increasing S/N, and they can be fitted with a first-order polynomial.

\[ \Delta A(Li)_{S/N} = a_0 + a_1 \times S/N. \]  

The fitting coefficients, \(a_0\) and \(a_1\), can be found in Table 1.

Figure 9. The deviations of the lithium abundances derived by changing stellar parameters with \(\Delta T_{\text{eff}} = +100\) K (a), \(\Delta \log g = +0.25\) dex (b), \(\Delta [\text{Fe/H}] = +0.1\) dex (c), and \(\Delta \xi = +0.5\) km s\(^{-1}\) (d) as functions of their corresponding parameters. Red dots and vertical error bars are the mean and the standard deviation, and the bin sizes are 400 K, 0.4 dex, 0.3 dex, and 0.05 km s\(^{-1}\), respectively. The red dashed lines are the fit to the mean values with third-order polynomial (panels (a)–(c)) and first-order polynomial (panel (d)). The microturbulences are calculated with the empirical relations presented in Section 2. Only results from spectra with S/N > 200 are adopted.
| LAMOST_id | obs_id | Gaia DR2 source_id | R.A. (J2000) | Decl. (J2000) | Teff (K) | log g (dex) | [Fe/H] (dex) | S/N | A(Li) (dex) | δA(Li) (dex) | para_source |
|-----------|--------|-------------------|--------------|--------------|----------|----------|----------|------|---------|--------------|------------|
| LAMOST J000000.32 + 573710.2 | 695107025 | 422596679654113792 | 00:00:00.32 +57:37:10.2 | 6407 | 4.0 | –0.1 | 121 | 2.4 | 0.2 | L |
| LAMOST J000000.96 + 411611.6 | 596808097 | 2882275590828656384 | 00:00:00.96 +41:16:11.6 | 5155 | 3.6 | –0.3 | 241 | 1.0 | 0.2 | L |
| LAMOST J000011.90 + 003841.9 | 612410091 | 2738294680609708032 | 00:00:11.90 +00:38:41.9 | 4624 | 4.5 | –0.1 | 62 | 0.3 | 0.2 | L |
| LAMOST J000026.11 + 042646.9 | 682016169 | 2740418627837183360 | 00:00:26.11 +04:26:46.9 | 5462 | 4.6 | 0.3 | 38 | 1.6 | 0.2 | L |
| LAMOST J000032.76 + 002107.6 | 695916238 | 2738205104717716484 | 00:00:32.76 +00:21:07.6 | 5372 | 4.3 | –0.8 | 49 | 1.3 | 0.2 | L |
| LAMOST J000032.76 + 002107.6 | 695916238 | 2738205104717716484 | 00:00:32.76 +00:21:07.6 | 5372 | 4.3 | –0.8 | 49 | 1.3 | 0.2 | L |
| LAMOST J000034.04 + 095225.0 | 694503069 | 2765223575737038568 | 00:00:34.04 +09:52:25.0 | 5490 | 4.1 | 0.4 | 68 | 2.0 | 0.2 | L |
| LAMOST J000035.84 + 090210.1 | 694510214 | 2747114791084908768 | 00:00:35.84 +09:02:10.1 | 6080 | 4.4 | –0.2 | 136 | 2.6 | 0.2 | L |
| LAMOST J000042.90 + 005734.1 | 612410125 | 2738310039412786944 | 00:00:42.90 +00:57:34.1 | 6084 | 4.1 | –0.4 | 36 | 3.2 | 0.2 | L |
| LAMOST J000042.90 + 005734.1 | 612410125 | 2738310039412786944 | 00:00:42.90 +00:57:34.1 | 6084 | 4.1 | –0.4 | 36 | 3.2 | 0.2 | L |
| LAMOST J000043.49 + 091720.6 | 694503241 | 2747173030845956480 | 00:00:43.49 +09:17:20.6 | 5685 | 4.3 | –0.8 | 228 | 1.2 | 0.2 | L |
| LAMOST J000044.10 + 044910.7 | 682016057 | 274194251659335216 | 00:00:44.10 +04:49:10.7 | 5202 | 3.9 | 0.1 | 129 | 1.4 | 0.2 | L |
| LAMOST J000044.44 + 544016.3 | 609207025 | 42036970961624964 | 00:00:44.44 +54:40:16.3 | 5799 | 4.4 | –0.3 | 98 | 2.1 | 0.2 | L |
| LAMOST J000044.78 + 090400.0 | 694510207 | 2741115306485484032 | 00:00:44.78 +09:04:00.0 | 6296 | 4.0 | 0.0 | 271 | 1.8 | 0.2 | L |
| LAMOST J000045.04 + 085702.9 | 694510201 | 2747109671488394624 | 00:00:45.04 +08:57:02.9 | 5649 | 4.4 | –0.3 | 79 | 1.4 | 0.2 | L |
| LAMOST J000045.72 + 411411.5 | 598108078 | 2882277407599002368 | 00:00:45.72 +41:14:11.5 | 5826 | 4.2 | 0.1 | 41 | 2.0 | 0.2 | L |
| LAMOST J000045.72 + 411411.5 | 598108078 | 2882277407599002368 | 00:00:45.72 +41:14:11.5 | 5826 | 4.2 | 0.1 | 41 | 2.0 | 0.2 | L |
| LAMOST J000046.05 + 100534.5 | 694503109 | 2765261882819683848 | 00:00:46.05 +10:05:34.5 | 5809 | 4.1 | 0.2 | 120 | 2.4 | 0.2 | L |
| LAMOST J000047.56 + 003056.2 | 612410177 | 2738242178929502592 | 00:00:47.56 +00:30:56.2 | 4973 | 4.4 | 0.3 | 89 | 1.0 | 0.2 | A |
| LAMOST J000047.79 + 081951.0 | 694502035 | 2746863312164361088 | 00:00:47.79 +08:19:51.0 | 4820 | 2.9 | –0.4 | 225 | 0.8 | 0.2 | L |
| LAMOST J000051.36 + 410852.9 | 597408085 | 2882234262809766272 | 00:00:51.36 +41:08:52.9 | 6194 | 4.3 | 0.0 | 80 | 2.9 | 0.2 | L |
| LAMOST J000052.60 + 573549.7 | 596909576 | 422595888690565248 | 00:00:52.60 +57:35:49.7 | 4182 | 1.7 | –0.1 | 154 | 0.2 | 0.2 | L |
| LAMOST J000052.60 + 573549.7 | 596909576 | 422595888690565248 | 00:00:52.60 +57:35:49.7 | 4182 | 1.7 | –0.1 | 154 | 0.2 | 0.2 | L |
| LAMOST J000053.43 + 004059.4 | 612410090 | 273824809142217600 | 00:00:53.43 +00:40:59.4 | 5840 | 4.2 | –0.3 | 177 | 2.4 | 0.2 | A |

Note.

a The sources of stellar parameters, “L” represents LASP and “A” represents APOGEE.

(This table is available in its entirety in machine-readable form.)
5.2. Errors Due to the Uncertainties in the Stellar Parameters

The uncertainties in atmospheric parameters will introduce errors in our measurements, and the following analysis was performed separately for the two sets of stellar parameters adopted.

5.2.1. The LASP-SP

The LASP-SP have typical uncertainties of 100 K, 0.25 dex, and 0.10 dex for the effective temperature, surface gravity, and metallicity, respectively (Luo et al. 2015), and the typical uncertainty in microturbulent velocity calculated with the empirical relations is around 0.5 km s\(^{-1}\). To evaluate the influence of the uncertainties of stellar parameters on the lithium abundances, we recalculated them with a change of the effective temperature by +100 K, the surface gravity by +0.25 dex, the metallicity by +0.10 dex, and the microturbulence velocity by + 0.5 km s\(^{-1}\) for the spectra with S/N > 200, respectively. Variations of the obtained lithium abundances for the changes in stellar parameters are shown in Figure 9.

It is clear that the errors are large for cool stars, which may be caused by the stronger Li\(^{i}\) resonance line at lower \(T_{\text{eff}}\) (panel (a)). The uncertainties in log \(g\) will introduce negligible errors in the lithium abundance calculation (panel (b)). While the errors for metal-poor stars are smaller than those for metal-rich targets (panel (c)), which are due to the influence of a nearby Fe\(^{i}\) line. The uncertainties in \(\xi\) result in small errors in the derived lithium abundances (panel (d)). We fitted the mean values in these bins with a third-order polynomial as functions of \(T_{\text{eff}}\) and [Fe/H] and a first-order polynomial for \(\xi\), respectively.

\[
\Delta A(\text{Li})_{T_{\text{eff}}} = b_0 + b_1 \times T_{\text{eff}} + b_2 \times T_{\text{eff}}^2 + b_3 \times T_{\text{eff}}^3, 
\]

\[
\Delta A(\text{Li})_{[\text{Fe/H}]} = c_0 + c_1 \times [\text{Fe/H}] + c_2 \times [\text{Fe/H}]^2 + c_3 \times [\text{Fe/H}]^3, 
\]

\[
\Delta A(\text{Li})_\xi = d_0 + d_1 \times \xi.
\]

The fitting coefficients are also listed in Table 1. Therefore, the total error of lithium abundance for every spectrum in LASP-SP can be estimated as

\[
\Delta A(\text{Li}) = \sqrt{\Delta A(\text{Li})_{T_{\text{eff}}}^2 + \Delta A(\text{Li})_{[\text{Fe/H}]}^2 + \Delta A(\text{Li})_\xi^2}. 
\]

5.2.2. The APOGEE-SP

The APOGEE-SP are provided by APOGEE DR16. The mean errors of \(T_{\text{eff}}\), log \(g\), and [Fe/H] are 100 K, 0.07 dex, and 0.01 dex, respectively (Jönsson et al. 2020). Thus, the errors of lithium abundances due to the uncertainties in \(T_{\text{eff}}\) and \(\xi\) are similar to those of the LASP-SP, while the influences of uncertainties in log \(g\) and [Fe/H] are negligible. The total error of lithium abundance for every spectrum in APOGEE-SP is estimated as

\[
\Delta A(\text{Li}) = \sqrt{\Delta A(\text{Li})_{T_{\text{eff}}}^2 + \Delta A(\text{Li})_{\xi}^2}. 
\]

6. Results and Discussion

The lithium abundances derived from LAMOST MRS spectra by us are presented in Table 2. Columns 1 and 2 of Table 2 are the LAMOST\_ids and obs\_ids, respectively. The Gaia DR2 source\_ids are given in Column 3. Columns 6–8 are the stellar parameters. The S/Ns of the spectra are shown in Column 9, while the lithium abundances and their errors are given in Columns 10 and 11, the typical uncertainty is ~0.2 dex. The final column contains the sources of stellar parameters.

We present a histogram of lithium abundances in Figure 10, while the lithium abundances versus the stellar parameters are plotted in Figure 11. The distribution of the lithium abundance versus \(T_{\text{eff}}\) indicates that the detection limit of lithium abundance is sensitive to \(T_{\text{eff}}\), and this limit is about –1.0 dex for the coolest stars in our sample. Also, the lithium abundances are strongly correlated to the temperature for the majority of stars as shown in Figure 11(a), and a similar phenomenon can be found in GALAH DR3 (Buder et al. 2021). The histogram presents two clear peaks around +2.6 and +1.0 dex, respectively. The former one at +2.6 dex is dominated by hot dwarfs, which indicates the minimum of the stellar lithium depletion for \(F\) and \(G\) dwarfs, and this phenomenon has also been found in open clusters (Thorburn et al. 1993; Anthony-Twarog et al. 2009; Cummings et al. 2017) and field stars. The latter one at +1.0 dex is dominated by giants, which is consistent with the discovery reported in open clusters (Gilroy 1989; Anthony-Twarog et al. 2021). This result supports that a more severe lithium depletion happens in giant phase. While some dwarfs have lithium abundance even higher than that of the meteorites, Deliyannis et al. (2002) suggested that the upward diffusion may enrich the surface lithium in some dwarfs under a narrow effective temperature range. There are a small fraction of giants with lithium abundances higher than 1.5 dex, which are denominated as lithium-rich giants, most of them have log \(g\) ~ 2.4 dex. This result suggests the existence of lithium enrichment mechanisms in some giants (Casey et al. 2016).
7. Summary

In this work, we provide the lithium abundances for 294,857 spectra of 165,479 stars. We derived the lithium abundances from LAMOST MRS spectra using a template-matching method. By comparing the lithium abundances determined by our method with those from the high-resolution surveys, including Gaia-ESO and GALAH, a good consistency can be found. The typical error of our lithium abundances is ∼0.2 dex. The lithium abundance derived in this work will be helpful for understanding the physical mechanisms occurring inside stars that either deplete the surface stellar lithium or create and enhance the surface stellar lithium, which will be investigated in our forthcoming works.

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Software: TOPCAT (Taylor 2005), SPECTRUM (Gray 1999).

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References
Abia, C., Pavlenko, Y., & de Laverny, P. 1999, A&A, 351, 273
Amarsi, A. M., Lind, K., Osorio, Y., et al. 2020, A&A, 642, A62
Anthony-Twarog, B. J., Deliyannis, C. P., Twarog, B. A., et al. 2009, AJ, 138, 1171
Anthony-Twarog, B. J., Deliyannis, C. P., & Twarog, B. A. 2021, AJ, 161, 159
Anthony-Twarog, B. J., Lee-Brown, D. B., Deliyannis, C. P., et al. 2018, AJ, 155, 138
Asplund, M., Lambert, D. L., Nissen, P. E., Primas, F., & Smith, V. V. 2006, ApJ, 644, 229
Bensby, T., Feltzing, S., Yee, J. C., et al. 2020, A&A, 634, A130
Bensby, T., & Lind, K. 2018, A&A, 615, A151
Boesgaard, A. M., Deliyannis, C. P., Stephens, A., et al. 1998, ApJ, 492, 727
Boesgaard, A. M., Lum, M. G., Deliyannis, C. P., et al. 2016, ApJ, 830, 49
Boesgaard, A. M., Lum, M. G., & Deliyannis, C. P. 2020, ApJ, 888, 28
Boesgaard, A. M., Stephens, A., & Deliyannis, C. P. 2005, ApJ, 633, 398
Bonifacio, P., & Molaro, P. 1997, MNRAS, 285, 847
Bonifacio, P., Molaro, P., Sivarani, T., et al. 2007, A&A, 462, 851
Buder, S., Asplund, M., Duong, L., et al. 2018, MNRAS, 478, 4513
Buder, S., Sharma, S., Kas, J., et al. 2021, MNRAS, in press
Casey, A. R., Ho, A. Y. Q., Ness, M., et al. 2019, ApJ, 880, 125
Casey, A. R., Ruchti, G., Masseron, T., et al. 2016, MNRAS, 461, 3336
Castelli, F., & Kurucz, R. L. 2003, IUPS, 210, A20
Charbonnel, C., & Lagarde, N. 2010, A&A, 522, A10
Charbonnel, C., & Talon, S. 1999, A&A, 351, 635
Coc, A., Goriely, S., Xu, Y., Saimpert, M., & Vangioni, E. 2012, ApJ, 744, 158
Coc, A., Uzan, J.-P., & Vangioni, E. 2014, JCAP, 10, 050
Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, RAA, 12, 1197
Cummings, I. D., Deliyannis, C. P., Maderak, R. M., et al. 2017, AJ, 153, 128
Cyburt, R. H., Fields, B. D., & Olive, K. A. 2003, PhilB, 567, 227s
Cyburt, R. H., Fields, B. D., & Olive, K. A. 2008, JCAP, 0801, 012
Cyburt, R. H., Fields, B. D., Olive, K. A., & Yeh, T.-H. 2016, RvMP, 2016, 015004
Deepak, P. D. L., & Reddy, B. E. 2020, MNRAS, 494, 1348
Delgado Mena, E., Bertrán de Lis, S., Adebekyan, V. Z., et al. 2015, A&A, 576, A69
Deliyannis, C. P., Anthony-Twarog, B. J., Lee-Brown, D. B., et al. 2019, AJ, 158, 163
Deliyannis, C. P., Boesgaard, A. M., Stephens, A., et al. 1998, ApJL, 498, L147
Deliyannis, C. P., Demarque, P., & Kawalet, S. D. 1990, ApJS, 73, 21
Deliyannis, C. P., King, J. R., Boesgaard, A. M., et al. 1994, ApJL, 434, L71
Domogatskii, G. V., Eramzhian, R. A., & Nadezhin, D. K. 1978, Ap&SS, 58, 273
Deliyannis, C. P., Steinhauer, A., & Jeffries, R. D. 2002, ApJL, 577, L39

Figure 11. The lithium abundances versus T_{eff} (a), log g (b), and [Fe/H] (c).
Fields, B. D., Olive, K. A., Yeh, T.-H., & Young, C. 2020, JCAP, 03, 10
Fu, X., Romano, D., Bragaglia, A., et al. 2018, A&A, 610, A38
Gao, X., Lind, K., Amarsi, A. M., et al. 2018, MNRAS, 481, 2666
Gao, X., Lind, K., Amarsi, A. M., et al. 2020, MNRAS, 497, L30
Gao, Q., Shi, J.-R., Yan, H.-L., et al. 2019, ApJS, 245, 33
García Pérez, A. E., Allende Prieto, C., Holtzman, J. A., et al. 2016, AJ, 151, 144
Gilroy, K. K. 1989, ApJ, 347, 835
Gray, R. O. 1999, SPECTRUM: A stellar spectral synthesis program
Astrophysics Source Code Library, ascl:9910.002
Guiglion, G., de Laverny, P., Recio-Blanco, A., et al. 2016, A&A, 595, A18
Hartmann, D., Myers, J., Woosley, S., Hoffman, R., & Haxton, W. 1999, ASPC, 171, 235
Holtzman, J. A., Haselquist, S., Shetrone, M., et al. 2018, AJ, 156, 125
Hou, S. Q., He, J. J., Parikh, A., et al. 2017, ApJ, 834, 165
Izzo, L., Dellal Valle, M., Mason, E., et al. 2015, ApJL, 808, L14
Jönsson, H., Holtzman, J. A., Prieto, C. A., et al. 2020, AJ, 160, 120
Kajino, T., Kusakabe, M., Baha Balantekin, A., et al. 2012, in PoS (NIC XII), Nuclei in the Cosmos, ed. J. Lattanzio et al. (Trieste: PoS), 70
Kang, M. M., Hu, Y., Hu, H. B., & Zhu, S. H. 2019, ApJ, 873, 68
Korn, A. J. 2020, MmSAI, 91, 105
Kumar, Y. B., Reddy, B. E., Campbell, S. W., et al. 2020, Nature Astronomy, 4, 1059
Kusakabe, M., & Kawasaki, M. 2015, MNRAS, 446, 1597
Lemoine, M., Vangioni-Flam, E., & Cassé, M. 1998, ApJ, 499, 735
Lind, K., Primas, F., Charbonnel, C., Grundahl, F., & Asplund, M. 2009, A&A, 503, 545
Liu, C., Fu, J., Shi, J., et al. 2020, arXiv:2005.07210
Luo, A.-L., Zhao, Y.-H., Zhao, G., et al. 2015, RAA, 15, 1095
Mathews, G. J., Kedia, A., Sasankan, N., et al. 2020, MmSAI, 91, 29
Meneguzzi, M., Audouze, J., & Reeves, H. 1971, A&A, 15, 337
Molaro, P. 2008, ASPC, 390, 472
Molaro, P., Bonifacio, P., & Pasquini, L. 1997, MNRAS, 292, L1
Molaro, P., Izzo, L., Mason, E., Bonifacio, P., & Della Valle, M. 2016, MNRAS, 463, L117
Olive, K. A., Petitjean, P., Vangioni, E., & Silk, J. 2012, MNRAS, 426, 1427
Prantzos, N. 2012, A&A, 542, A67
Prantzos, N., de Laverny, P., Guiglion, G., Recio-Blanco, A., & Worley, C. C. 2017, A&A, 606, A132
Prugniel, P., & Souffrin, C. 2001, A&A, 369, 1048
Prugniel, P., Souffrin, C., Koleva, M., et al. 2007, arXiv:astro-ph/0703658
Ramírez, I., Fish, J. R., Lambert, D. L., & Allende Prieto, C. 2012, ApJ, 756, 46
Randich, S., Pasquini, L., Franciosini, E., et al. 2020, A&A, 640, L1
Reeves, H., Fowler, W. A., & Hoyle, F. 1970, Natur, 226, 727
Romano, D., Matteucci, F., Ventura, P., & D’Antona, F. 2001, A&A, 374, 646
Ryan, S. G., & Deliyannis, C. P. 1995, ApJ, 453, 819
Sasankan, N., Kedia, A., Kusakabe, M., & Mathews, G. J. 2020, PhRvD, 101, 123532
Selvelli, P., Molaro, P., & Izzo, L. 2018, MNRAS, 481, 2261
Shi, J. R., Gehren, T., Zhang, H. W., et al. 2007, A&A, 465, 587
Singh, R., Reddy, B. E., Bharat Kumar, Y., & Antia, H. M. 2019, ApJL, 878, L21
Smith, V. V., & Lambert, D. 1989, ApJL, 345, L75
Smith, V. V., & Lambert, D. 1990, ApJL, 361, L69
Spergel, D. N., Verde, L., Peiris, H. V., et al. 2003, ApJS, 148, 175
Spite, F., & Spite, M. 1982, A&A, 115, 357
Stonkutė, E., Chorniy, Y., Tautvaïsiene, G., et al. 2020, AJ, 159, 90
Tajitsu, A., Sadakane, K., Naito, H., Arai, A., & Aoki, W. 2015, Natur, 518, 381
Tajitsu, A., Sadakane, K., Naito, H., et al. 2016, ApJ, 818, 191
Taylor, M. B. 2005, ASPC, 347, 29
Thorburn, J. A., Hobbs, L. M., Deliyannis, C. P., et al. 1993, ApJ, 415, 150
Yan, H.-L., Shi, J.-R., Zhou, Y.-T., et al. 2018, NatAs, 2, 790
Yan, H.-L., Zhou, Y.-T., Zhang, X., et al. 2021, NatAs, 5, 86
Yoshida, T., & Tajitsu, T. 2005, NuPhA, 758, 35
Yoshida, T., Terasawa, M., Tajitsu, T., & Sumiyoshi, K. 2004, ApJ, 600, 204
Zerjal, M., Ireland, M. J., Nordlander, T., et al. 2019, MNRAS, 484, 4591
Zhao, G., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, RAA, 12, 723