Lithium, Carbon, and Oxygen Abundances of Hyades F–G Type Stars

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Abstract

In an attempt to carry out a systematic study on the behavior of the photospheric abundances of Li, C, and O (along with Fe) for Hyades main-sequence stars in the $T_{\text{eff}}$ range of $\sim 5000$–$7000$ K, we conducted an extensive spectrum-synthesis analysis applied to four spectral regions (comprising lines of Fe-group elements, Li $i$ 6708 line, C $i$ 7111–7119 lines, and O $i$ 6156–8 lines) based on the high-dispersion spectra of 68 selected F–G type stars belonging to this cluster. The abundances of C and O turned out to be fairly uniform in a marginally supersolar level such like the case of Fe: $\langle [C/H] \rangle = +0.15$ ($\sigma = 0.08$), $\langle [O/H] \rangle = +0.22$ ($\sigma = 0.14$), and $\langle [Fe/H] \rangle = +0.11$ ($\sigma = 0.08$), suggesting that the primordial abundances are almost retained for these elements. Strictly, however, they show a slightly increasing trend with a decrease in $T_{\text{eff}}$ (typically on the order of $\sim 10^{-4}$ dex K$^{-1}$); while this might be due to an improper choice of atmospheric parameters, we found it hard to give a quantitatively reasonable explanation. Regarding Li, we confirmed the well-known $T_{\text{eff}}$-dependent trend in the Li abundance reported so far (a conspicuous Li-trough at $T_{\text{eff}} < \sim 6000$ K), which means that the surface Li of Hyades stars is essentially controlled only by $T_{\text{eff}}$ and other parameters such as the rotational velocity are almost irrelevant.

Key words: Galaxy: open clusters and associations: individual (Hyades) — stars: abundances — stars: atmospheres — stars: late-type — stars: rotation

1. Introduction

1.1. Chemical Abundances of Hyades Cluster Stars

Since stars belonging to a cluster are considered to have formed almost at the same time out of chemically near-homogeneous material, spectroscopically studying the photospheric abundances of cluster stars can provide us with valuable information on the primordial gas (chemical composition, degree of homogeneity, etc.) as well as physical processes that may posteriori affect surface abundances (e.g., mixing/segregation in the stellar envelope).

Above all, the Hyades cluster (comprising A–M stars, its age and distance being precisely determined as $6.25 \times 10^8$ yr and 47 pc, respectively; cf. Perrymann et al. 1998; its metallicity is known to be slightly supersolar at $[Fe/H] \sim 0.1$–0.2; cf. Takeda 2008) is one of the most suitable galactic open clusters for this objective because of its proximity and well-established parameters of member stars.

The purpose of this article is to report the results of our new systematic abundance studies on Li (a key element whose abundance reflects mixing history of the envelope because of its fragile nature) as well as C and O (most

$[X/H]$ means the differential abundance of element X of a star relative to that of the Sun; i.e., $[X/H] = A(X)_\ast - A(X)_\odot$. Here, $A(X)$ denotes the logarithmic (number) abundance of an element X with the usual normalization of $A(H) = 12.00$.}

* Based on data collected at Okayama Astrophysical Observatory (NAOJ, Japan).
abundant metals playing important roles in the galactic chemical evolution) for a number of F–G type stars of the Hyades cluster.

1.2. Oxygen

Oxygen abundances of Hyades main-sequence stars are not yet sufficiently well understood. To describe the situation on this matter, stars have to be divided into two groups to be separately treated: A-type stars (\(T_{\text{eff}} \gtrsim 7000\) K) and FGK-type stars (\(T_{\text{eff}} \lesssim 7000\) K).

1.2.1. \([\text{O}/\text{H}]\) in Hyades A stars

While it is certain that Hyades A-type stars (including Am stars) in the \(T_{\text{eff}}\) range of \(\sim 7000–9000\) K show diversified O-abundances in their photospheres (being anti-correlated with Fe in the sense that a deficit of O is accompanied by an excess of Fe), presumably due to the process of chemical segregation (atomic diffusion) in the stellar envelope (e.g., Richer et al. 2000), the issue of how this anomaly (Am peculiarity) is triggered is still somewhat controversial (i.e., only the rotational velocity is responsible? or some other factors are involved?).

Takeda and Sadakane (1997) reported the existence of a \(v_\text{rot} \sin i\)-dependence of \([\text{O}/\text{H}]\) (a positive correlation at \(v_\text{rot} \sin i \lesssim 100\) km s\(^{-1}\)) from their spectrum-fitting analysis of the O I 7771–5 triplet lines on 18 Hyades A-type stars.

However, Varenne and Monier (1999) did not corroborate this relation in their analysis for 19 Hyades A dwarfs using O I 6155–8 lines, though a tendency of lower \([\text{O}/\text{H}]\) for A-type slower rotators (\(v_\text{rot} \sin i \lesssim 100\) km s\(^{-1}\)) is observed (cf. their figure 5 therein).

Nevertheless, Takeda et al. (2009) reconfirmed the clear rotation-dependent trend of \([\text{O}/\text{H}]\) in 23 Hyades A-type stars (i.e., an increasing tendency from \(\sim -0.5\) to \(\sim 0\) with an increase in \(v_\text{rot} \sin i\) at 0 km s\(^{-1}\) \(\lesssim v_\text{rot} \sin i \lesssim 100\) km s\(^{-1}\)) while an almost constant \([\text{O}/\text{H}]\) of \(\sim 0.05 \pm 0.10\) at \(v_\text{rot} \sin i \lesssim 100\) km s\(^{-1}\); cf. figure 8a therein) based on the O I 6155–8 lines as used by Varenne and Monier (1999).

Yet, Gebran et al. (2010) concluded in their reanalysis of 16 Hyades A-stars that any meaningful correlation does not exist between \([\text{O}/\text{H}]\) and \(v_\text{rot} \sin i\), again the same conclusion as that of Varenne and Monier (1999). However, since their figure 7 apparently exhibits a trend of subsolar \([\text{O}/\text{H}]\) for A-stars of lower \(v_\text{rot} \sin i\), this might rather be a matter of definition in their using the word of ‘correlation’ or ‘dependence.’

1.2.2. \([\text{O}/\text{H}]\) in Hyades FGK stars

Meanwhile, when it comes to discussing the primordial O-abundance of this cluster, it is necessary to establish the precise \([\text{O}/\text{H}]\) values of unevolved F–G–K dwarfs. Unfortunately, however, despite a number of investigations done so far, any consensus has not yet been accomplished:

- Tomkin and Lambert (1978) studied two Hyades F-type stars (45 Tau = HD 26462 and HD 27561) using O I 9260–9266 lines and obtained \([\text{O}/\text{H}] = +0.18\) and +0.02, respectively.

- García-Lopéz et al. (1993) reported from their analysis of O I 7771-5 lines that the mean \([\text{O}/\text{H}]\) of F-type stars is slightly subsolar (\(-0.05\) or \(-0.10\) depending on the sample selection).

- King (1993) concluded based on O I 7771–5 lines that mean \([\text{O}/\text{H}]\) of four Hyades late-F stars is supersolar (\([\text{O}/\text{H}] = 0.27\)).

- King and Hiltgen’s (1996) analysis of O I 6300 line on two Hyades early K dwarfs yielded \([\text{O}/\text{H}] \sim +0.15\).

- Takeda et al. (1998) derived the mean \([\text{O}/\text{H}]\) of \(\sim +0.1\) for 11 Hyades F stars based on the O I 8446 line.

- Analysis of F-type stars (7000 K \(\gtrsim T_{\text{eff}} \gtrsim 6000\) K) by Varenne and Monier (1999) suggested a marginally supersolar trend of \([\text{O}/\text{H}]\) ranging from 0.0 to +0.3.

- Schuler et al. (2006a,b) made an extensive O-abundance study for many Hyades G–K dwarfs by using O I 7771–5, O I 6300, and CO lines; they found a considerable increase of supersolar \([\text{O}/\text{H}]\) (especially for those from O I 7771–5 lines) toward decreasing \(T_{\text{eff}}\) at \(T_{\text{eff}} \lesssim 5500\) K (presumably due to the enhanced chromospheric activity which makes the classical treatment inapplicable), and could not accomplish any consistent solution for the oxygen abundance of the cluster.

- Gebran et al.’s (2010) analysis of F-type stars (7000 K \(\gtrsim T_{\text{eff}} \gtrsim 6000\) K) implied a rather large diversity (around \([\text{O}/\text{H}] \sim 0\)) amounting to \(\sim 0.4\) dex.

Given this complicated situation, a new comprehensive study may be worth carrying out. So far, we have been involved with investigating the oxygen abundances of field main-sequence stars by using the spectrum-fitting technique applied to O I 6156–8 lines (Takeda et al. 1999 [late B and A stars]; Takeda & Honda 2005 [from late F to early K stars]; Takeda et al. 2010 [B stars]). These high-excitation permitted O I lines are regarded to be well suitable for abundance determinations because of (1) their visibility over a wide \(T_{\text{eff}}\) range, (2) no concern for any strong non-LTE effect, and (3) being presumably insensitive to chromospheric activity because of their deep-forming nature. We, therefore, decided to conduct an extensive oxygen abundance study for a number of early F to late G stars of this cluster by using these O I 6156–8 lines.

—Do \([\text{O}/\text{H}]\) values of Hyades F–G stars are sufficiently uniform? Or, alternatively, do they show any trend as in the case of A stars?

—How are they compared with other metals? A supersolar tendency is also observed?

1.3. Carbon

Regarding carbon, available abundance studies for Hyades stars are rather insufficient compared to the case of oxygen.

First, C abundances of Hyades A-type stars (9000 K \(\gtrsim T_{\text{eff}} \gtrsim 7500\) K) were derived by Varenne and Monier (1999)
as well as Gebran et al. (2010) based on C i lines such as the one at 5052.17 Å, and they obtained almost the same results: [C/H] shows a diversity between \( \sim -0.8 \) and \( \sim 0.1 \) (where Am stars tend to show particularly large deficiencies), though its dependence on \( v_c \sin i \) is not clear as is the case for [O/H].

Then, as to the [C/H] values of Hyades F-stars (\( T_{\text{eff}} \lesssim 7000 \) K) we know only a few published studies.

— Tomkin and Lambert (1978) derived [C/H] values for two Hyades F-type stars (45 Tau = HD 26462 and HD 27561) by using C i lines in the red and near-IR region (such as those at 7111–9 Å) and obtained slightly supersolar values of [C/H] = +0.06 and +0.18, respectively.

— Friel and Boesgaard (1990) carried out C-abundance determinations for 13 Hyades F-stars of \( T_{\text{eff}} \sim 6000–7000 \) K by using the C i 6587, 7110, 7111–9 Å lines and derived the marginally supersolar result on the average (\( \langle [\text{C/H}] \rangle \approx +0.04 \); with a standard deviation of 0.07), which means [C/Fe] \( \approx 0.0 \) as Fe also shows a slight excess of this amount.

— Varenne and Monier (1999) as well as Gebran et al. (2010) (mentioned above) concluded that carbon in Hyades F-type stars is essentially homogeneous and near solar ([C/H] \( \sim 0 \)) with only a small scatter of \( \lesssim 0.1–0.2 \) dex.

Recently, the abundance (especially in relation to oxygen) in solar-type stars has acquired growing astrophysical interest among astronomers, given its important role played in the chemical evolution of the Galaxy. Takeda and Honda (2005) showed in their study of 160 FGK stars that [C/O] ratio is supersolar \( (> 0) \) at the metal-rich regime ([Fe/H] \( > 0 \)) with its extent progressively increasing toward a higher [Fe/H], which was first pointed out by Gustafsson et al. (1999), because the decreasing rate of [C/H] with [Fe/H] is slower than that of [O/H]. \(^2\) It is thus interesting to check whether the [C/O] ratio of Hyades stars ([Fe/H] \( \sim 0.1–0.2 \)) is supersolar as in nearby field FGK stars of [Fe/H] \( > 0 \). This will provide us with important information for understanding the chemical composition of the primordial gas, from which cluster stars were formed.

Accordingly, it makes our alternative aim of this study to establish the abundances of carbon for Hyades F–G stars as precisely as possible, in order to examine the degree of homogeneity (how large is the star-to-star scatter of [C/H]?) and the abundance ratios relative to the Sun (how much are the values of [C/H] and [C/O] on the average?). For this purpose, we apply spectrum-fitting to C i lines at 7111–7119 Å (also used by Friel and Boesgaard 1990), where several C i lines of appreciable strengths are confined and reliable C-abundance determinations may be expected.

\(^2\) The [C/O] ratio may also be an important key for spectroscopically sorting out planet-host stars, as recently claimed by Petigura and Marcy (2011).

14. Lithium

Besides, this study also focuses on lithium of Hyades F–G stars, because we are particularly interested in this element in connection with our recent work and the Li i 6708 line is measurable in our spectra.

Actually, a number of investigations have been published so far on the Li abundances of Hyades late-A through early-K dwarfs (Herbig 1965; Wallerstein et al. 1965; Cayrel et al. 1984; Boesgaard & Tripicco 1986; Boesgaard & Budge 1988; Burkhart & Coupry 1989, 2000; Soderblom et al. 1990; Thorburn et al. 1993), and the qualitative trend of A(Li) is quite well established: that is, a conspicuous Li chasm in early-F stars around \( T_{\text{eff}} \sim 6300–6800 \) K, a progressive decline of A(Li) with a decrease in \( T_{\text{eff}} \) for G stars at \( T_{\text{eff}} \lesssim 6000 \) K.

Yet, we point out that most of these studies tend to place emphasis on stars of specific spectral types (e.g., either A/Am stars, F stars, or G stars), and are based on classical-type analysis using equivalent widths (EW). It would be worthwhile to revisit the Li abundances of early-F through late-G stars covering a wider \( T_{\text{eff}} \) range by applying the spectrum-synthesis technique to the Li i 6708 line and taking into account the non-LTE effect, in a consistent manner such as done by Takeda and Kawanomoto (2005), which may help to clarify their trend as well as dependence (if any) on stellar parameters to a quantitatively higher precision. Specifically, we would like to find answers to the following questions, for example, resulting from our recent related work:

— Do the A(Li) values of Hyades F stars connect well with those of A-type stars which we recently determined (Takeda et al. 2012)?

— Is the A(Li) vs. \( v_c \sin i \) relation established for field solar-analog stars (Takeda et al. 2007, 2010) also observed in Hyades early-G stars?

1.5. Construction of This Paper

The remainder of this paper is organized as follows. The adopted observational data for 68 Hyades F–G stars are explained in section 2, while the assigned atmospheric parameters and model atmospheres are mentioned in sections 3 and 4, respectively. Section 5 describes the procedures of our abundance determinations, which are made up of spectrum-synthesis fitting for finding the best-fit solutions and inverse evaluations of equivalent widths (from which changes to parameter perturbations are estimated). The finally resulting abundances of Li, C, and O (along with Fe) and their trends are discussed in section 6. The conclusions are summarized in section 7.

2. Observational Data

The targets of this study are 68 main-sequence stars of F–G spectral type (corresponding to \( T_{\text{eff}} \sim 5000–7000 \) K) belonging to the Hyades cluster, which were selected from de Bruijne, Hoogerwerf, and de Zeeuw’s (2001) catalogue (“table1.dat” therein), as given in table 1. These program stars are plotted on the color–magnitude diagram in
The reduction of the spectra (bias subtraction, flat-fielding, scattered-light subtraction, spectrum extraction, wavelength calibration, and continuum normalization) was performed by using the “echelle” package of the software IRAF\(^4\) in a standard manner. For most of the targets, we could accomplish sufficiently high S/N ratio of \(\sim 200–300\).

Besides, since the region comprising C i 7111–9 lines (which we used for C-abundance determination) is partly contaminated by telluric water vapor lines, we removed them by dividing the raw spectrum of each star by a relevant spectrum of \(\alpha\) Leo (rapid rotator) by using the IRAF task telluric. A demonstrative example of this elimination process is depicted in figure 2. Actually, the telluric features could be satisfactorily cleared away by this procedure for all the 68 targets.

### 3. Atmospheric Parameters

Regarding the effective temperature \((T_{\text{eff}})\) and surface gravity \((\log g)\) for each of the 68 target stars, we adopted the values directly evaluated from mass, radius, and luminosity by de Bruijne, Hoogerwerf, and de Zeeuw (2001) and given in their “table1.dat”. This is due to our policy of making our analysis as consistently as possible for all the program stars covering a rather wide \(T_{\text{eff}}\) range, since widely used spectroscopic determinations of \(T_{\text{eff}}\) and \(\log g\) using Fe i and Fe ii lines can not be applied to F-type stars of larger rotational velocity (owing to the difficulties in equivalent-width measurements) even if applicable to sharp-lined (mostly G-type) stars. These \(T_{\text{eff}}\) and \(\log g\) values are given in table 1, as well as in the electronic table E1 (tableE1.dat). The resulting \(T_{\text{eff}}\) vs. \(B-V\) relation is displayed in figure 1b, where we can recognize a tight relationship between these two quantities.

As for the assignment of the microturbulence \((\xi)\) to each star, we invoked the following empirical relations,\(^5\) which

\[^3\] This was the situation (only one CCD) at the time of observations in 2003–2004. At present, HIDES has three mosaicced 4K×2K CCDs with the whole wavelength coverage of \(\sim 3700\) Å.

\[^4\] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

\[^5\] These empirical approximations for \(\xi\) applicable to FGK stars were already reported in Takeda (2008; cf. page 314 therein). Note, however, the inequality signs discriminating two \(T_{\text{eff}}\)
were established from the linear-regression analysis on the \( \xi \) results of 160 FGK stars determined by Takeda et al. (2005).

\[
\xi = 9.9 \times 10^{-4} T_{\text{eff}} - 0.41 \log g - 2.92 \quad (1)
\]
(for \( T_{\text{eff}} > 5800 \) K)

\[
\xi = 5.6 \times 10^{-4} T_{\text{eff}} - 0.31 \log g - 0.79 \quad (2)
\]
(for \( T_{\text{eff}} < 5800 \) K),

where \( \xi, T_{\text{eff}}, g \) are in the units of km s\(^{-1}\), K, and cm s\(^{-2}\), respectively. How well these equations (1) and (2) approximate the \( \xi \) results of Takeda et al. (2005) is demonstrated in figures 3a and 3b, where we can see that these formulae can reproduce the real data within a few tenths km s\(^{-1}\) for most cases. Thus, the \( \xi \) values for the 68 program stars were computed from \( T_{\text{eff}} \) and \( \log g \) by using these relations, as presented in table 1.

It is interesting to compare such assigned values of \( T_{\text{eff}}, \log g, \) and \( \xi \) (which we call as “standard parameters”) with those spectroscopically determined based on the conventional method using Fe I and Fe II lines. As an example, such a comparison with those of Paulson et al.’s (2003) spectroscopic parameters for Hyades G-type stars (40 stars in common with our sample) is displayed in figure 4a–4c. In addition, we also tried establishing spectroscopic parameters by ourselves for selected 37 comparatively sharp-lined G dwarfs (out of total 68 samples) based on the equivalent widths of \( \sim 100 \) Fe I lines and \( \sim 10 \) Fe II lines measured on the same spectra as used in this study, and the results were briefly reported in Takeda (2008).

So, we here compare them with the standard parameters in figures 5a–5c, while presenting the detailed data of these spectroscopic parameters in electronic table E2 (tableE2.dat). We note the following characteristics from these figures.

- Spectroscopically determined \( T_{\text{eff}} \) tends to be systematically higher by the adopted \( T_{\text{eff}} \) by \( \sim 100 \) K (figures 4a and 5a).
- Some spectroscopically determined \( \log g \) are appreciably lower (by \( \sim 0.2–0.3 \) dex) than the adopted \( \log g \), though overall agreement is not so bad within \( \sim \pm 0.1 \) dex (figures 4b and 5b).
- Spectroscopically determined \( \xi \) tends to be somewhat lower than our empirical formula values by \( \lesssim 0.5 \) km s\(^{-1}\) in Paulson et al.’s (2003) results (cf. figure 4c), while this inequality is just reversed in our results where spectroscopic \( \xi \) values are higher by a few tenths km s\(^{-1}\) than the formula values (figure 5c).

4. Model Atmospheres

The model atmosphere for each star was then constructed by two-dimensionally interpolating Kurucz’s (1993) ATLAS9 model grid in terms of \( T_{\text{eff}} \) and \( \log g \), where we applied the solar-metallicity models computed with a microturbulent velocity of 2 km s\(^{-1}\) (“ap00k2.dat”).

These original ATLAS9 models approximately include the convective overshooting effect in an attempt to simulate the real convection as possible. It has been occasionally argued, however, that this treatment may cause inconsistencies with observational quantities (e.g., colors or Balmer line profiles) and even the classical pure mixing-length treatment “without overshooting” would be a better choice (e.g., Castelli et al. 1997). Since lines tend to become somewhat weaker in “with overshooting” atmospheres as compared to “without overshooting” cases because of the lessened temperature gradient in the lower part of the atmosphere, some difference may be expected in resulting abundances between these two cases, especially for comparative higher \( T_{\text{eff}} \) stars (i.e., early G to late A; cf. Fig. 24 of Castelli et al. 1997) where the convection zone due to hydrogen ionization comes close to the bottom of the atmosphere.

In order to maintain consistency with our previous
work, we adopt the original ATLAS9 models “with overshooting” as the standard models throughout this study. However, we also tried deriving abundances in our spectrum-fitting analysis by applying “no overshooting” models\(^6\) (as well as “with overshooting” models) and obtained the corresponding abundance changes, \(\delta \text{over} \equiv A(\text{no-overshoot}) - A(\text{with-overshoot})\), in order to see whether and how the difference in this treatment may cause any appreciable effect.

5. Procedures of Analysis

5.1. Synthetic Spectrum Fitting

Abundance determinations using our spectral-synthesis code, which is originally based on Kurucz’s (1993) WIDTH9 program, were carried out by applying the best-fit solution search algorithm (Takeda 1995), while simultaneously varying the abundances of several key elements \((A_1, A_2, \ldots)\), macrobroadening parameter \((v_M)\), and the radial-velocity (wavelength) shift \((\Delta \lambda)\).

The macrobroadening parameter \((v_M)\) represents the combined effects of instrumental broadening, macroturbulence, and rotational velocity. As to the form of macrobroadening function, \(M(v)\), we applied either one of the following two functions (rotational-broadening function for the uniform-disk case and Gaussian function), depending on the appearance of spectral-line shapes judged by eye-inspection:

\[
M(v) \propto \sqrt{1 - (v/v_M)^2} \quad (3)
\]

\[
M(v) \propto \exp\left[-(v/v_M)^2\right] \quad (4)
\]

Specifically, our spectrum fitting was conducted for the following four wavelength regions, where the elements whose abundances were treated as variables are enumerated in each bracket:

1. 6080–6089 Å (Si, Ti, V, Fe, Co, Ni) [primarily for determinations of \(v_M\) and Fe abundance]
2. 6703–6709 Å (Li, Fe) including Li i 6708 lines [for Li abundance determination]
3. 7110–7121 Å (C, Fe, Ni) including C i 7111–9 lines [for C abundance determination]
4. 6156–6159 Å (O, Ti, Fe) including O i 6156–8 lines [for O abundance determination]

Note that analyses for the 6080–6089 Å as well as 6156–6159 Å regions are the same as in Takeda and Honda (2005). Similarly, the analysis for the 6707–6709 Å region is the same as in Takeda and Kawanomoto (2005).

Regarding the atomic data of spectral lines (wavelengths, excitation potentials, oscillator strengths, etc.), we basically invoked the compilations of Kurucz and Bell (1995). However, pre-adjustments of several \(\log gf\) values were necessary (i.e., use of empirically determined solar \(gf\) values) in order to accomplish a satisfactory match.

\(^6\) Available from Kurucz’s web site (http://kurucz.harvard.edu/) as “ap00k2mean.dat”.

\(^7\) This lower limit was raised up to \(\sim 6707\) Å for G stars \((\text{Teff} \lesssim 5800\ \text{K})\) because of the increased complexity of the spectra.
between the observed and theoretical spectrum. The finally adopted atomic parameters of important spectral lines are presented in table 2. As for the damping parameters (which are unimportant in the present case because very strong lines are absent in the relevant wavelength regions), the data given in Kurucz and Bell (1995) were used; if not available therein, we invoked the default treatment of Kurucz’s (1993) WIDTH9 program.

Note that we assumed LTE for all lines at this stage of synthetic spectrum-fitting and that this analysis was performed not only with the standard “convective overshooting” model but also with the “no-overshooting” model, in order to check the difference (\(\delta_{\text{NRT}}\)) between these two treatments (cf. section 4).

Although the convergence of the solutions turned out fairly successful for most of the cases, we encountered with some cases where convergence was poor (e.g., oscillatory) or abundance solution of some specific element even became unstable and divergent. When any abundance parameter could not be established, we fixed it at the solar value and retried the calculation. After the solutions have been established, we checked by eye whether the synthetic theoretical spectrum satisfactorily matches the observed spectrum. If the convergence of any abundance solution was not sufficiently good, or if the consistency between theoretical and observed spectrum did not appear satisfactorily good at the relevant line position, we judged this abundance solution to be of “low reliability.” How the theoretically good at the relevant line position, we judged this abundance solution to be of “low reliability.”

In order to check the difference (\(\delta_{\text{NRT}}\)) between these two.

5.2. Macrobroadening Parameter and Rotational Velocity

It would be appropriate here to remark that the solution of the macrobroadening parameter \(v_M\) derived as a by-product of spectrum fitting can be a fairly good indicator of projected rotational velocity \(v_r \sin i\), on the condition that \(v_r \sin i\) is not too small.

If the rotational velocity is large and spectral lines show rounded shapes, we used equation (3) (rotational broadening function), and this choice corresponds to the solutions of \(v_M \gtrsim 16\, \text{km s}^{-1}\) (cf. table 1). In this case, \(v_M\) can naturally be regarded as essentially equivalent to \(v_r \sin i\), since the contributions of instrumental broadening and macroturbulence (both are on the order of several \(\text{km s}^{-1}\)) are anyhow negligible compared to this extent.

Further, we would point out that \(v_M\) is still a good approximation of \(v_r \sin i\) also for the slower rotation case where we used equation (4) (Gaussian broadening function). This is because, if we require that the FWHMs of the rotation function \(\sqrt{1 - (v/v_r \sin i)^2}\) and the Gaussian function \(\exp[-(v/v_r)^2]\) be equal, we obtain the relation \(v_r \sin i \approx 0.94v_r \sin i\) (cf. footnote 12 of Takeda et al. 2008), which guarantees a practical equality between these two.

So, as far as \(v_r \sin i\) is not so small compared with the instrumental width or the macroturbulence width, \(v_M \sim v_r \sin i\) is not a bad approximation, irrespective of the adopted broadening functions. It should be bear in mind, however, that this relation does not hold any more at \(v_M \lesssim 5\, \text{km s}^{-1}\) where the contributions of the instrumental width as well as the macroturbulence width become progressively important, though \(v_M\) might still be regarded as a “qualitative measure” of \(v_r \sin i\) even in such a slow-rotator regime.

5.3. Equivalent Widths and Abundance Uncertainties

While the synthetic spectrum fitting directly yielded the abundance solutions of Li, C, and O (the main purpose of this study), this approach is not necessarily suitable when one wants to evaluate the extent of non-LTE corrections or to study the abundance sensitivity to changing the atmospheric parameters (i.e., it is rather tedious to repeat the fitting process again and again for different assumptions or different atmospheric parameters). Therefore, with the help of Kurucz’s (1993) WIDTH9 program, we computed the equivalent widths for Li (6708 (EW6708), C 7113 (EW7113; the strongest line among the C I lines at 7111–9 A), and O i 6158 (EW6158), “inversely” from the abundance solutions (resulting from spectrum synthesis) along with the adopted atmospheric model/parameters, which are much easier to handle. Based on such evaluated EW values, the non-LTE \(A^\text{NLTE}\) as well as LTE abundances \(A^{\text{LTE}}\) were freshly computed to derive the non-LTE correction \(\Delta = A^\text{LTE} - A^{\text{NLTE}}\). The procedures for non-LTE calculations are described in Takeda and Kawanomoto (2005) (for Li) as well as Takeda and Honda (2005) (for C and O), which should be consulted for the details. For the case where \(A(\text{Li})\) could not be determined (which we encountered for several F stars at the “Li-gap”), we first guessed the upper-limit of \(A(\text{Li})\).

\[
EW_{6708}^{\text{UL}} = \sqrt{h^2 + 150^2}/(S/N) \quad (\text{m}A) \quad (5)
\]
\[
h \equiv 6708 \times 1000 \times (v_M/c) \quad (\text{m}A), \quad (6)
\]

(where 150 mA is the approximate intrinsic width defined by the separation of the components; cf. Takeda & Honda (2005)).

This WIDTH9 program had been considerably modified by Y. T. in various respects; e.g., inclusion of non-LTE effects, treatment of total equivalent width for multi-component lines; etc.
Kawanomoto 2005), from which the upper limit of \( A(\text{Li}) \) was derived.

We then estimated the uncertainties in \( A(\text{Li}), A(\text{C}) \), and \( A(\text{O}) \) by repeating the analysis on the EW values while perturbing the standard atmospheric parameters interchangeably by \( \pm 100 \) K in \( T_{\text{eff}} \), \( \pm 0.1 \) dex in \( \log g \), and \( \pm 0.5 \) km s\(^{-1} \) in \( \xi \) (which are considered to be typical magnitudes of ambiguities; cf. section 3). Figures 10 (Li), 11 (C), and 12 (O) graphically show the resulting non-LTE abundances \((A_{\text{NLTE}})\), equivalent widths (EW), non-LTE corrections \((\Delta_{\text{NLTE}})\), abundance changes caused by using the no-overshooting model \((\delta_{\text{nover}})\), and abundance variations in response to parameter changes \((\delta_T, \delta_g, \delta_\xi)\), as functions of \( T_{\text{eff}} \). While such obtained non-LTE abundances of Li, C, and O are given in table 1, the complete results of abundances, corrections, and perturbations are presented in electronic table E1, where the abundance changes for Fe \((\delta_{\text{nover}}, \delta_T, \delta_g, \delta_\xi)\), which were obtained by repeating the fitting analysis in this case) are also given. Hereinafter, we often omit the superscript “NLTE” of \( A_{\text{NLTE}} \) for denoting the non-LTE abundances of Li, C, and O.

6. Discussion

6.1. \( T_{\text{eff}} \)-Dependence Problem in \( A(\text{C}), A(\text{O}), \) and \( A(\text{Fe}) \)

We first examined whether C and O (elements of our primary concern) show essentially the same abundances along the Hyades main sequence. A close inspection of figures 11b and 12b revealed that \( A(\text{C}) \) as well as \( A(\text{O}) \) shows a slightly increasing tendency with a decrease in \( T_{\text{eff}} \). Excluding the unreliable determinations (denoted by open circles), we found from the linear-regression analysis\(^9\) \( dA(\text{C})/dT_{\text{eff}} = -8.2 \times 10^{-5} \) (dex K\(^{-1} \)) for C (54 stars) and \( dA(\text{O})/dT_{\text{eff}} = -1.2 \times 10^{-4} \) (dex K\(^{-1} \)) for O (49 stars), which means a change of \( \pm 0.1 \) dex over a span of \( \sim 1000 \) K.

Interestingly, quite a similar trend is seen in \( A(\text{Fe}) \) given in table 1 (64 stars), for which we again found a gradient of \( dA(\text{Fe})/dT_{\text{eff}} = -1.0 \times 10^{-4} \) (dex K\(^{-1} \)). We note, however, that the situation is not necessarily the same for other Fe group elements. Figure 13 shows the \( A \) vs. \( T_{\text{eff}} \) relations for six elements (Si, Ti, V, Fe, Co, and Ni) derived from the 6080–6089 \( \AA \) fitting analysis (figure 6). We can recognize from this figure that any systematic \( T_{\text{eff}} \)-dependence is absent for \( A(\text{Ti}) \) and \( A(\text{Co}) \) while \( A(\text{Ni}) \) exhibits a steeper gradient than \( A(\text{Fe}) \).

It would be natural to suspect in the first place that this trend may be due to inadequacies in the adopted model atmospheres or some improper choice of atmospheric parameters, for which several possibilities may be considered:

— The use of “no-overshooting” model instead of the standard “overshooting” model can not be the remedy for this trend, because this acts as a negative correction \((\delta_{\text{nover}} < 0)\) and its extent \(|\delta_{\text{nover}}|\) being slightly larger toward higher \( T_{\text{eff}} \) (cf. section 4); i.e., the gradient is even more exaggerated (though only marginally) by applying this correction (figures 11d, 12d, and 13).

— Meanwhile, the effect of increasing \( T_{\text{eff}} \) (which is probable as spectroscopically determined \( T_{\text{eff}} \) turned out to be somewhat larger than the adopted standard \( T_{\text{eff}} \) by \( \sim 100 \) K) can cause a \( T_{\text{eff}} \)-dependent correction in the direction of suppressing this tendency at least for C and O (cf. figures 11e and 12e), though not for Fe. Yet, the extent seems still quantitatively insufficient; i.e., even the case of C where the largest \( T_{\text{eff}} \)-dependence is observed in \( \delta_T \), the gradient of \( d\delta_T/dT_{\text{eff}} \) is as \( \sim 1/2–1/3 \) as required to remove the trend.

— Regarding the gravity effect, abundances are practi-
cally insensitive to a change in \( \log g \) (typically a few hundredths dex for \( \Delta \log g \approx +0.1 \)) and this correction hardly depends on \( T_{\text{eff}} \) (figures 11f and 12f).

— As mentioned in section 3, since our spectroscopically determined \( \xi \) tends to be somewhat larger (by a few tenths km s\(^{-1}\)) than the adopted \( \xi \) based on equations (1) and (2), increasing this parameter may be worth consideration. We note that the abundances of C and O barely depend on the choice of \( \xi \) because they are light elements with large thermal velocities which makes the contribution of non-thermal velocities insignificant (figures 11g and 12g). However, the abundance of Fe (along with those of Ti, V, and Ni) derived from 6080–6089 Å fitting is appreciably reduced by an increase of \( \xi \), and the extent of this downward correction is larger for lower \( T_{\text{eff}} \) stars where lines are stronger and more saturated, which is just in the right direction, as shown in figure 13 (\( \delta_{\xi+} \) for \( \Delta \xi = +0.5 \text{ km s}^{-1} \) is \( \sim -0.02 \text{ dex} \), \( \sim -0.04 \text{ dex} \), and \( \sim -0.15 \text{ dex} \) at \( T_{\text{eff}} \approx 7000 \text{ K} \), 6000 K, and 5000 K, respectively; cf. electronic table E1). This could be an explanation (at least partly) for the \( T_{\text{eff}} \)-dependence of \( A(\text{Fe}) \), though it is not necessarily satisfactory from a quantitative point of view.

Thus, despite these considerations, we could not trace down the reason for the systematic \( T_{\text{eff}} \)-dependence in \( A(\text{C}) \), \( A(\text{O}) \), and \( A(\text{Fe}) \). Accordingly, we might as well put the possibility (even if small) into our mind that this trend could be real. In the discussion of the differential abundances relative to the Sun and their averages over the sample stars (subsection 6.2), we use these original abundance results (given in table 1) as they are. Accordingly, the existence of such a slight systematic effect should be kept in mind: this may cause ambiguities of \( \lesssim 0.1 \text{ dex} \) level in the averaged abundance depending on which \( T_{\text{eff}} \) range is used.

6.2. \([\text{C/H}], [\text{O/H}], \text{ and } [\text{Fe/H}]\) of Hyades Stars

We discuss the C, O, and Fe abundances of Hyades F–G stars in comparison with the solar composition in order to quantitatively establish their differential metallicities, with an aim to settle the complicated situation regarding [C/H] and [O/H] mentioned in subsections 1.2 and 1.3. As to the reference solar abundances of O and Fe, we adopt \( A_\odot(\text{O}) = 8.81 \) and \( A_\odot(\text{Fe}) = 7.53 \) from Takeda and Honda (2005), who derived these values by applying (in exactly the same manner as in this study) the 6156–6158 Å fitting and 6080–6089 Å fitting to the moon spectra (cf. section 4 therein). Meanwhile, the solar carbon abundance was newly determined in this study by applying the 7110–7121 Å fitting to the moon spectrum (taken at this observational period along with other spectra) with the

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**Fig. 11.** C \( \lambda 7113 \)-related quantities plotted against \( T_{\text{eff}} \). Note that the ordinate scale of panels (c)–(g) is as \( \sim \) 7 times expanded as that of panel (b). That the sign of \( \delta_{\xi+} \) is positive (which contradicts the usual trend) at \( T_{\text{eff}} \lesssim 6000 \text{ K} \) in panel (g) is interpreted as due to a special effect seen in weak lines on the linear part of the curve of growth (cf. subsection 3.2 in Takeda 1994). Otherwise, the same as in figure 10.

**Fig. 12.** O \( \lambda 6158 \)-related quantities plotted against \( T_{\text{eff}} \). Note that the ordinate scale of panels (c)–(g) is as \( \sim \) 7 times expanded as that of panel (b). Otherwise, the same as in figure 10.
Fig. 13. Abundances of Si, Ti, V, Fe, Co, and Ni (derived from 6080–6089 Å fitting) plotted against \( T_{\text{eff}} \). The results obtained from the ATLAS9 model atmospheres with convective overshooting (which we adopted as the standard models) are shown by filled symbols, while those derived with no-overshooting models and those corresponding to an increase of microturbulent velocity by 0.5 km s\(^{-1}\) are plotted by open symbols and crosses, respectively. Vertical offsets of +1.0, +0.5, −0.5, and −0.5 are applied to A(Si), A(Ti), A(Co), and A(V), respectively, as described in the figure. The results in the \( T_{\text{eff}} \) range of 6800 K \( \gtrsim \) \( T_{\text{eff}} \) \( \gtrsim \) 6300 K (including stars of comparatively higher rotation) are subject to larger uncertainties (especially for Ti, Co, V; as recognized by their considerable dispersions), and thus should not be taken too seriously.

Solar model atmosphere (ATLAS9 model with convective overshooting, \( T_{\text{eff}} = 5780 \) K, \( \log g = 4.44 \), solar metallicity, and \( \xi = 1 \) km s\(^{-1}\)), from which we obtained \( A_{\odot}(C) = 8.51 \) (\( EW_{713.0} = 21.2 \) mÅ, \( \Delta_{\text{LTE}} = −0.01 \)).

The resulting [Fe/H], [C/H], [O/H], and [C/O] (≡ [C/H] − [O/H]) are plotted against \( T_{\text{eff}} \) in figures 14a–14d, respectively. Apart from the slight systematic gradient discussed in subsection 6.1, we can recognize from these figures that the abundances of Fe, C, and O are reasonably homogeneous with a marginally supersolar tendency. In the following discussion of the mean abundance and standard deviation, we exclude the unreliable determinations (open circles) and confine only to the reliable results (filled circles).

The mean [Fe/H] (over 64 data) turned out to be \( \langle [\text{Fe/H}] \rangle = +0.11 \) with the standard deviation (\( \sigma \)) of 0.08. So far, a number of published studies on Hyades [Fe/H] values have yielded results between +0.1 (lower scale) and +0.2 (higher scale) (see, e.g., figure 32.8 in Takeda 2008). While Takeda (2008) derived a higher-scale value of [Fe/H] = +0.19 (\( \sigma = 0.05 \)) based on a precise differential study for Hyades early-G stars of near-solar \( T_{\text{eff}} \) (\( \sim 5500–6000 \) K), our present study covering F–G stars implies a result near to the lower scale. We consider, however, that this difference may be due to the existence of a weak \( T_{\text{eff}} \)-dependent gradient (subsection 6.1), which would make the averaged abundance over F–G stars slightly lower than that only for G-type stars.

Regarding [C/H] and [O/H], we obtained \( \langle [\text{C/H}] \rangle = +0.15 \) (\( \sigma = 0.08 \)) from 54 stars and \( \langle [\text{O/H}] \rangle = +0.22 \) (\( \sigma = 0.14 \)) from 49 stars. This means that C as well as O are slightly supersolar in Hyades by \( \sim +0.1–0.2 \) dex just as the case for Fe, and that [C/H] and [O/H] are almost uniform over 7000 K \( \gtrsim \) \( T_{\text{eff}} \) \( \gtrsim \) 5000 K with only a small dispersion of \( \sim ±0.1 \) dex. As to this conclusion of weakly positive nature of [C/H] and [O/H] by \( ±0.2 \) dex for this cluster, we can see that most of the published values of [C/H] and [O/H] for F–G stars summarized in section 1 are more or less consistent with our results, except for several studies which suggested near-solar or subsolar C or O.

\[ X = \frac{A_{\odot}(X) - A_\text{s.s.}(X)}{A_\text{s.s.}(X)} \]
A four stars appear to show a weak tendency of decreasing A stars including 6 Hyades A/Am stars, among which (2012) recently studied the Li abundances of sharp-lined 6.3. Behavior of Li Abundance solar-system abundance of A σ of 1 T−1999 for C; Gebran et al. 2010 for C and O). No. ] Li, C, and O Abundances of Hyades F–G Stars 11 is ⟨[C/O]⟩ averaged over the metallicity range of 0 A ⟨[Fe/H]⟩ < 0.2 is ⟨[C/O]⟩ = +0.03 with σ = 0.026 (Takeda & Honda 2005) and ⟨[C/O]⟩ = +0.025 with σ = 0.118 (Petitg & Marcy 2011). This implies that the difference of ∼0.1 dex (= −0.07 − 0.03) from the main trend is still on the order of σ and thus should not be taken seriously.

6.3. Behavior of Li Abundance

Finally, we examine the abundances of Li, especially in terms of their dependence on Teff and the rotational velocity. Our A(Li) results and their differences from the solar system abundance (A_{obs} = 3.31; Anders & Grevesse 1989) are plotted against Teff in figures 10b and 14e, respectively. We can see from these figures that the well-known characteristics in the A(Li) vs. Teff relation established in previous studies (see the references cited in subsection 1.4) has been firmly corroborated in this study; i.e., an apparent Li chasm at 6700 K ≳ Teff ≳ 6300 K and a progressive decline of A(Li) with a decrease in Teff at Teff ≳ 6000 K. Although our analysis is different from the previous work in taking account of the non-LTE corrections varying from ∼−0.1 dex to ∼+0.2 dex over the Teff range of ∼5000–7000 K (cf. figure 10c; the difference of the correction sign is because of the fact that the dilution of the source function is important at higher Teff, while the overionization becomes more significant at lower Teff; cf. section 3 in Takeda & Kawanomoto 2005), these corrections are quantitatively insignificant compared to the considerably large dynamic range of A(Li) amounting up to ∼3 dex.

Thus, our results superficially look quite similar to what has been reported so far.

We note in figure 14e that A(Li) at Teff ≳ 6800 K (on the higher Teff side out of the Li chasm) is almost the solar-system abundance of A(Li)_{obs} = 3.31. Takeda et al. (2012) recently studied the Li abundances of sharp-lined A stars including 6 Hyades A/Am stars, among which four stars appear to show a weak tendency of decreasing A(Li) from ∼3.3 (Teff ≈ 8000 K) to ∼3.0 (Teff ≈ 7200–7500 K), though Li was depleted and unmeasurable in two Am stars. Although we once suspected that this might be a continuous extension of the “Li gap” to A-stars regime (Teff ≳ 7000 K), the present result (preservation of the primordial Li abundance in stars of 7000 K ≳ Teff ≳ 6800 K) implies that the Li depletion mechanism seen in A-type stars is different from the physical process responsible for the Li gap of Hyades F-type stars.

It was one of our main aims to examine if the Li abundances of Hyades stars show any dependence upon the rotational velocity, especially for early G-type stars where the evident correlation between A(Li) and v sin i is observed in field solar-analog stars (Takeda et al. 2007, 2010). However, as seen from the tight decline of A(Li) from Teff ≳ 6000 K to ∼5500 K (figure 10b) without showing any considerable scatter seen in field stars of this Teff range (cf. figure 8 of Takeda & Kawanomoto 2005; figure 9a of Takeda et al. 2007), it may be natural to consider that A(Li) depends only on Teff without any relevance to other parameters, as least for Hyades G-type stars. To confirm this, our A(Li) results are plotted against v_M (measure of v sin i; cf. subsection 5.2) in figures 15b (all stars) and 15c (only stars of Teff < 6000 K, all of which have v_M < 7 km s^{-1}), from which we can read the following characteristics:— We can not see any significant v_M-dependence in A(Li) of F stars (Teff > 6000 K) showing a large range of v_M (∼10–70 km s^{-1}).— Regarding G-type stars (Teff < 6000 K), we see an increasing tendency of A(Li) with an increase in v_M (figure 15c). We believe, however, that this is nothing but an apparent effect due to the Teff-dependence of v_M (i.e., a decrease of v_M toward a lower Teff; cf. figure 15a). Thus, we conclude that the Li abundances of Hyades G-type stars are essentially controlled only by Teff. This means that the characteristic v sin i-dependence of A(Li) observed in field solar-analog stars with ages of ∼(10–100)×10^8 yr (cf. figure 5g in Takeda et al. 2010) is absent in younger Hyades stars (with ages of ∼6 × 10^8 yr), which may suggest that such a rotation-dependent anomaly is produced during the main-sequence life time, not in the pre-main-sequence phase.

7. Conclusion

The C and O abundances of main-sequence stars in the Hyades cluster are not yet well established despite their astrophysical importance, for which a number of previous studies reported different results. Also, the abundances of Li (key element for investigating the physical process in the envelope) and Fe (representative of metallicity) are worth reinvestigation by taking this opportunity. Motivated by this situation, we decided to carry out a systematic abundance study of these elements for Hyades main-sequence stars in the Teff range of ∼5000–7000 K.

Practically, we derived these abundances by applying a spectrum-synthesis analysis to four spectral regions at 6080–6089 Å, 6707–6709 Å, 7110–7121 Å, and 6157–6159 Å (comprising lines of Fe-group elements, Li i 6708
stars reported so far (i.e., a conspicuous Li-trough at 6700 K \( \gtrsim T_{\text{eff}} \gtrsim 6300 \) K and a progressive decline with a decrease in \( T_{\text{eff}} \) below \( < 6000 \) K). Since \( A(\text{Li}) \) at 7000 K \( \gtrsim T_{\text{eff}} \gtrsim 6800 \) K (a zone encompassed by the deficiency of Li in A/Am stars and the Li chasm of F stars) is almost the solar-system abundance, the Li depletion mechanism seen in A-type stars is considered to be different from the physical process responsible for the Li gap of Hyades F-type stars.

We concluded that the the surface Li of Hyades stars is essentially controlled only by \( T_{\text{eff}} \) and other parameters such as the rotational velocity are almost irrelevant. A positive correlation between \( A(\text{Li}) \) and stellar rotation, which is observed in field solar-analog stars, is not seen in these younger early G-type stars of the Hyades cluster. This may impose an important constraint on the time scale in the build-up of such a rotation-dependent Li anomaly.

Fig. 15. Relations between \( v_{\text{M}} \) (macrobroadening velocity derived from the 6080–6089 Å fitting; measure of \( v_{\text{e}} \sin i \)), \( T_{\text{eff}} \), and \( A(\text{Li}) \). (a) \( v_{\text{M}} \) vs. \( T_{\text{eff}} \), (b) \( A(\text{Li}) \) vs. \( v_{\text{M}} \) (all data), and (c) \( A(\text{Li}) \) vs. \( v_{\text{M}} \) (only for \( T_{\text{eff}} < 6000 \) K data). Stars for \( T_{\text{eff}} > 6000 \) K and \( T_{\text{eff}} < 6000 \) K are distinguished by (red) squares and (blue) circles, respectively. Open symbols and downward triangles denote that these \( A(\text{Li}) \) results are uncertain values and upper-limit values, respectively.

It turned out that these C, O, and Fe abundances similarly exhibit a marginal \( T_{\text{eff}} \)-dependent gradient (i.e., slightly increasing with a decrease in \( T_{\text{eff}} \); typically on the order of \( \sim 10^{-4} \) dex K\(^{-1}\)) although this might be nothing but an apparent effect due to an improper choice of atmospheric parameters, we found it hard to give a quantitatively reasonable explanation.

Apart from this small systematic gradient, the abundances of C, O, and Fe in these Hyades stars were found to be fairly uniform and marginally supersolar with only a small scatter of \( \sim 0.1 \) dex: \( \langle [\text{C}/\text{H}] \rangle = +0.15 \) (\( \sigma = 0.08 \)), \( \langle [\text{O}/\text{H}] \rangle = +0.22 \) (\( \sigma = 0.14 \)), and \( \langle [\text{Fe}/\text{H}] \rangle = +0.11 \) (\( \sigma = 0.08 \)), suggesting that the primordial abundances are almost retained.

Regarding Li, we confirmed the well-known \( T_{\text{eff}} \)-dependent trend in the Li abundances of Hyades F–G
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Fig. 6. Synthetic spectrum fitting at the 6080–6089 Å region accomplished by adjusting the macrobroadening velocity ($v_M$; which is a measure of $v_{\text{rot}}\sin i$) along with the abundances of Si, Ti, V, Fe, Co, and Ni. The best-fit theoretical spectra are shown by solid lines, while the observed data are plotted by symbols. In each panel, the spectra are arranged in the descending order of $T_{\text{eff}}$ as in table 1, and an appropriate offset is applied to each spectrum (indicated by the HD number) relative to the adjacent one.
Fig. 7. Synthetic spectrum fitting at the 6703–6709 Å region comprising the Li i 6708 line for determining the abundance of Li (and Fe). Otherwise, the same as in figure 6.
Fig. 8. Synthetic spectrum fitting at the 7110–7121 Å region for determining the abundance of C (along with Fe and Ni). Otherwise, the same as in figure 6.
Fig. 9. Synthetic spectrum fitting at the 6156–6159 Å region for determining the abundance of O (along with Fe). Otherwise, the same as in figure 6.
Table 1. Basic parameters of 68 target stars and the resulting abundances.

| HD     | $M_V$ | $B-V$ | $T_{eff}$ | log $g$ | $\xi$ | $v_M$ type | $A(Fe)$ | $A(Li)$ | $A(C)$ | $A(O)$ |
|--------|-------|-------|-----------|---------|-------|------------|---------|---------|--------|--------|
| 024340 | 5.28  | 0.53  | 7000      | 4.30    | 2.2   | 0.61       | 4.74    | 3.19    | 8.49   | 9.06   |
| 026326  | 5.37  | 0.53  | 6764      | 4.30    | 2.2   | 0.61       | 4.55    | 3.16    | 8.54   | 9.18   |
| 026081  | 5.66  | 0.40  | 6795      | 4.32    | 2.0   | 0.78       | 7.66    | 3.25    | 8.61   | 8.85   |
| 026911  | 5.07  | 0.40  | 6783      | 4.32    | 2.0   | 0.78       | 7.60 < 1.36 | 8.58   | 8.89   |
| 028406  | 5.38  | 0.42  | 6744      | 4.33    | 2.0   | 0.78       | 7.58 < 1.35 | 8.64   | 8.91   |
| 025102  | 5.38  | 0.42  | 6705      | 4.33    | 1.9   | 0.82       | 7.55 < 1.95 | 8.81   | 9.01   |
| 028736  | 5.19  | 0.42  | 6693      | 4.34    | 1.9   | 0.78       | 7.52 < 1.53 | 8.65   | 8.96   |
| 028911  | 5.19  | 0.42  | 6669      | 4.34    | 2.0   | 0.78       | 7.51 < 1.95 | 8.81   | 9.01   |
| 031825  | 5.39  | 0.42  | 6656      | 4.34    | 1.9   | 0.82       | 7.54 < 1.95 | 8.66   | 8.96   |
| 027534  | 5.29  | 0.44  | 6598      | 4.35    | 1.8   | 0.78       | 7.52 < 1.95 | 8.64   | 8.89   |
| 029225  | 5.45  | 0.44  | 6593      | 4.35    | 1.8   | 0.78       | 7.61 < 1.95 | 8.64   | 8.89   |
| 027848  | 5.32  | 0.45  | 6558      | 4.35    | 1.8   | 0.78       | 7.60 < 1.95 | 8.64   | 8.89   |
| 018404  | 5.29  | 0.41  | 6714      | 4.33    | 1.8   | 0.78       | 7.56 < 1.95 | 8.64   | 8.89   |
| 028433  | 5.19  | 0.41  | 6676      | 4.34    | 2.0   | 0.78       | 7.54 < 1.95 | 8.64   | 8.89   |
| 029582  | 5.19  | 0.41  | 6649      | 4.34    | 2.0   | 0.78       | 7.52 < 1.95 | 8.64   | 8.89   |
| Columns 1 through 6 are presented the HD number, absolute visual magnitude, effective temperature (in K), logarithmic surface gravity (in cm s$^{-2}$) and microturbulence (in km s$^{-1}$). Columns 7 nd 8 give the macrobroadening velocity (measure of $v_M$ sin $i$) and the type of the adopted broadening function ($\cdot$ rotational function, $\cdot$ Gaussian function), respectively. The final abundances of $A(Fe)$, $A(Li)$, $A(C)$, and $A(O)$ are in columns 9–12 (in the usual normalization of $H = 12.00$), where uncertain values are parenthesized and upper-limit values are expressed in italics. The stars are arranged in the order of descending $T_{eff}$. |
Table 2. Atomic parameters of important lines relevant for spectrum fitting.

| Species | λ  | χ  | log gf | Remark     |
|---------|----|----|--------|------------|
|         |    |    |        |            |
| [6080–6089 Å fitting] | | | | |
| V i     | 6081.441 | 1.05 | −0.58 | (adjusted) |
| Co i    | 6082.422 | 3.51 | −0.52 |            |
| Fe i    | 6082.708 | 2.22 | −3.57 |            |
| Fe ii   | 6084.111 | 3.20 | −3.81 |            |
| Ti i    | 6085.228 | 1.05 | −1.35 |            |
| Fe i    | 6085.260 | 2.76 | −3.21 |            |
| Ni i    | 6086.276 | 4.27 | −0.53 |            |
| Co i    | 6086.658 | 3.41 | −1.04 |            |
| Si i    | 6087.805 | 5.87 | −1.60 |            |
|         |    |    |        |            |
| [6703–6709 Å fitting] | | | | |
| Fe i    | 6703.568 | 2.76 | −3.02 | (adjusted) |
| Fe i    | 6705.101 | 4.61 | −1.02 | (adjusted) |
| Fe i    | 6707.441 | 4.61 | −2.35 |            |
| Li i    | 6707.756 | 0.00 | −0.43 | Li 6708    |
| Li i    | 6707.768 | 0.00 | −0.21 | Li 6708    |
| Li i    | 6707.907 | 0.00 | −0.93 | Li 6708    |
| Li i    | 6707.908 | 0.00 | −1.16 | Li 6708    |
| Li i    | 6707.919 | 0.00 | −0.71 | Li 6708    |
| Li i    | 6707.920 | 0.00 | −0.93 | Li 6708    |
|         |    |    |        |            |
| [7110–7121 Å fitting] | | | | |
| Ni i    | 7110.892 | 1.94 | −2.88 | (adjusted) |
| C i     | 7111.472 | 8.64 | −1.24 | (adjusted) |
| Fe i    | 7112.168 | 2.99 | −2.89 | (adjusted) |
| C i     | 7113.178 | 8.65 | −0.80 | (adjusted), C 7113 |
| C i     | 7115.172 | 8.64 | −0.96 | (adjusted) |
| C i     | 7116.991 | 8.65 | −0.91 |            |
| Fe i    | 7118.119 | 5.01 | −1.39 | (adjusted) |
| C i     | 7119.656 | 8.64 | −1.13 | (adjusted) |
| Fe i    | 7120.022 | 4.56 | −1.91 | (adjusted) |
|         |    |    |        |            |
| [6156–6159 Å fitting] | | | | |
| O i     | 6156.737 | 10.74 | −1.52 |            |
| O i     | 6156.755 | 10.74 | −0.93 |            |
| O i     | 6156.778 | 10.74 | −0.73 |            |
| Fe i    | 6157.725 | 4.08 | −1.26 |            |
| O i     | 6158.149 | 10.74 | −1.89 | O 6158     |
| O i     | 6158.172 | 10.74 | −1.03 | O 6158     |
| O i     | 6158.187 | 10.73 | −0.44 | O 6158     |

Note. λ is the air wavelength (in Å), χ is the lower excitation potential (in eV), and log gf is the logarithm of g (statistical weight of the lower level) times f (absorption oscillator strength). These data were taken primarily from the compilation of Kurucz and Bell (1995), though empirically adjusted “solar gf values” were applied in several cases (remarked as “adjusted” in column 5). Regarding lithium, we considered only the component lines of $^7$Li, neglecting those of $^6$Li.