Metallicity Measurements of Pleiades Young Dwarfs

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(Received 2009 February 9; accepted 2009 May 21)

Abstract

We present metallicity analyses of A, F, and G stars in the Pleiades cluster. High-resolution spectroscopic observations of 25 stars were made with the HIDES spectrograph on the Okayama 1.88-m telescope and the GAOES spectrograph on the Gunma 1.5-m telescope. The resultant optical spectra had an S/N of 70–220. We measured the equivalent widths of ~60 neutral iron and ~15 single-ionized iron absorption lines to determine stellar parameters and metallicities. We derived the metallicities of 22 stars by adapting the method of equivalent-width measurements. The average metallicity was \( +0.03 \pm 0.05 \) dex. The dispersion was comparable to the statistical uncertainties of the metallicity measurements; in addition, the metallicities of all 22 stars fell within the dispersion range, indicating their uniform metallicities. A comparison of our results with previous studies confirmed a high probability of metallicity homogeneity in Pleiades.

Key words: open clusters and associations: individual (Pleiades) — stars: abundances — techniques: high-resolution spectroscopy

1. Introduction

“An open cluster is a star aggregate born in a molecular cloud. Although the cluster members have different masses, their ages and initial chemical compositions are thought to be the same” (Bennett et al. 2003). Introductory astronomy books often explain open clusters in this way. Chemical abundance analysis of open clusters yields important information about the chemical history of the Galaxy. Since the 1970’s, spectroscopists have actively studied chemical abundances of numerous open clusters with a wide range of age, including \(~2.5\)-Gyr M 67 (e.g., Cohen 1980) and \( \sim 30 \) Myr \( \alpha \) Persei cluster (e.g., Boesgaard 1989). They compared the chemical abundances of several open clusters (e.g., Boesgaard 1989; Friel & Janes 1993) and analyzed age-metallicity correlation and abundance gradients in the galactic disk.

A study of star-to-star abundance scatter in an open cluster is also important to understand chemical evolution from a molecular cloud to star formation. Paulson et al. (2003, hereafter P03) was the very first study of how to analyze chemical homogeneity in an open cluster by high-resolution spectroscopic observations of a large number of cluster members. Using Keck/HIRES, they analyzed the abundances of seven heavy elements, such as iron, \( \alpha \) elements, and Fe-peak elements, for 56 Hyades F, G, and K stars. Fe-peak elements and \( \alpha \) elements are produced by Type Ia and Type II supernovae. In fact, nothing indicates the presence of any supernovae around the Hyades; hence, the Hyades members probably retain their initial elemental abundances. Finally, P03 demonstrated the chemical homogeneity of the Hyades by showing that 53 of 56 stars have uniform metallicities and other abundances. The three other stars were identified as non-members of the Hyades from a membership analysis of stars around the Hyades region (e.g., Perryman et al. 1998). However, no study has investigated the chemical homogeneity of any other cluster by measuring the abundances of a large number of members. Any quantitative conclusion in discussions of the chemical homogeneities of open clusters requires an investigation of the chemical properties of many clusters of varying ages, cluster member numbers, stellar densities, binary fractions, and cluster environments.

The open cluster targeted in this paper, the Pleiades, is the third-closest open cluster. It consists of \(~300\) members (Schilbach et al. 1995) at an age of about 120 Myr (Basri et al. 1996). The chemical abundances of Pleiades stars have been determined by several groups over the past few decades. Among eight studies measuring stellar metallicities (Boesgaard et al. 1988; Boesgaard 1989; Boesgaard & Friel 1990; Boesgaard 2005; Burkhart & Coupry 1997; Gebran & Monier 2008; King et al. 2000; Wilden et al. 2002), Wilden et al. (2002, hereafter W02) and Boesgaard (2005, hereafter B05) achieved high-precision metallicity measurements using Keck/HIRES. W02 observed 16 G and K stars, finding 14 stars with uniform metallicities \( ([\text{Fe}/\text{H}]) = 0.10 \pm 0.02 \) dex, assuming the solar iron abundance to be 7.54. B05 investigated 20 F and G stars, including four from W02 (Boesgaard, in private communication), and also concluded that the metallicities were uniform, with a value of \(+0.06 \pm 0.02\) dex. Although both studies agreed on the basic metallicity homogeneity of the Pleiades, the inconsistency between the average metallicities of W02 and B05 should be resolved to continue the discussion of the chemical homogeneity in the Pleiades.

In this work we analyzed high-resolution spectra of 25 Pleiades members. Abundance analyses of other elements...
will be presented in a future paper. In section 2, we explain our observations and data-reduction procedures. Section 3 presents our metallicity measurement methods, and our results and discussion are presented in section 4.

2. Observations and Reduction

The sample for this study was constructed to satisfy the following criteria:

1. More than 65% likelihood of being a Pleiades member as evaluated by its proper motion (Belikov et al. 1998; Kharchenko et al. 2004; Schilbach et al. 1995).
2. A brightness of from 8th to 11th magnitude in the $V$ band. Pleiades members with such brightness are of spectral types A, F, and G.
3. A low probability of binarity, as determined from photometric observations, radial velocity measurements, and direct imaging observations (Bouvier et al. 1997; Kähler 1999; Mermilliod et al. 1992, 1997; Raboud & Mermilliod 1998; Rosvick et al. 1992).

With these criteria in mind, we chose 25 stars to observe (table 1). Our samples included H II 470, a Pleiades star that has been previously studied by Boesgaard and Friel (1990, hereafter BF90), in order to estimate the systematic uncertainties in our result due to instrument and analysis differences.

We made spectroscopic observations at the Okayama Astrophysical Observatory (OAO) and the Gunma Astronomical Observatory (GAO) in 2006 and 2007 (see table 1). We used the High-Dispersion Echelle Spectrograph (HIDES) for the OAO 188 cm reflector and the Gunma Astronomical Observatory Echelle Spectrograph (GAOES) for the GAO 150 cm reflector. With a spectral resolution of $R \sim 40000$, the obtained spectra had a wavelength range of 5300–6600 Å and 4900–6700 Å with HIDES and GAOES, respectively. To avoid cosmic-ray contamination, we limited each exposure time to less than 30 min for HIDES and less than 60 min for GAOES. The total exposure times were 30 min to 7 hr, depending on the stellar brightness. We obtained spectra with S/N ratios of 70–220 by combining data. We obtained 10 bias, and 10 flat-field frames were obtained at either the beginning or the end of every night. Wavelength calibration data were taken 3 to 5 times every night. Halogen and thorium–argon lamps, respectively, were used to take the flat-fields and wavelength calibration data.

Data reduction was carried out through bias-subtraction, flat-fielding, cosmic-ray removal, scattered-light subtraction, spectrum extraction, and continuum normalization by using

Table 1. Samples and observation log.

<table>
<thead>
<tr>
<th>H II</th>
<th>Name</th>
<th>$V$</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>Night</th>
<th>Exposure time</th>
<th>S/N</th>
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<td>03 44 20.1</td>
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<td>Jan/07, GAO</td>
<td>60 × 6</td>
<td>90</td>
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<tr>
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<td>HD 23289</td>
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<td>03 44 51.2</td>
<td>+24 47 46</td>
<td>Jan/07, OAO</td>
<td>30 × 2</td>
<td>120</td>
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<tr>
<td>470</td>
<td>HD 23289</td>
<td>9.01</td>
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<td>+24 47 46</td>
<td>Jan/06, GAO</td>
<td>30 × 2</td>
<td>170</td>
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<tr>
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<td>Melotte 22, SSHJ 302</td>
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<tr>
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<td>170</td>
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<tr>
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<td>03 49 56.5</td>
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<td>60 × 6</td>
<td>220</td>
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IRAF. For samples observed several times to archive high S/N ratios, data were combined after calibrating wavelength drifts due to telluric motion and instrumental instability.

3. Analysis

We analyzed the equivalent width (W) method in order to derive stellar metallicity. This method requires precise measurements of equivalent widths of iron absorption lines and the determination of stellar parameters, such as the effective temperature (Teff), surface gravity (log g), and microturbulence velocity (vt). We explain the equivalent width measurements and spectroscopic analysis of stellar parameters and metallicity in following subsections.

We employed the software code SPTOOL (Takeda et al. 2002) for this analysis. The model spectrum that this program generated is based on Kurucz’s ATLAS9 atmospheric model (Kurucz 1993), which is an LTE standard parallel-plain atmospheric model. Recent studies measuring the chemical abundances of young open clusters, such as Hyades (Schuler et al. 2006), indicated that high excitation lines and lines of ionized elements were stronger than predicted by simple models. Schuler et al. (2006) suggested that this difference was caused by the presence of photospheric spots and faculae in young dwarfs. However, this problem occurs in G, K dwarfs, with Teff ≤ 6000 K, and reduces in warmer G dwarfs, with Teff ≥ 5500 K. Our sample had a Teff warmer than 5800 K; hence, we considered that this program to be negligible for our analysis.

3.1. Equivalent Width Measurements

Accurate metallicity determination requires selections of iron absorption lines with accurate atomic parameters, such as the line wavelength, excitation potential (ξ), and oscillator strength (gf value). We selected 66 neutral iron (Fe I) and 14 single-ionized iron (Fe II) absorption lines, the atomic parameters of which were determined from laboratory experiments (e.g., Grevesse & Sauval 1999; Raassen & Uylings 1998). Strong wings in lines with W ≥ 130 mÅ prevented precise measurements of their equivalent widths. We only used lines whose equivalent widths were less than 120 mÅ in our analyses (table 2).

Our samples included stars with fast rotational velocities, (v sin i ≥ 30 km s⁻¹). Our selected Fe lines in those stars’ spectra were blended with neighboring lines, and hence it was difficult to directly measure the equivalent widths of the lines. Therefore, considering the method used by Takeda et al. (2005), equivalent widths of selected Fe lines were inversely measured by the spectral synthesis method. The procedure of the equivalent width measurement is explained below.

Abundance derivation with spectral synthesis:

The spectral synthesis method fits synthetic spectra to observed spectral lines and derives abundances of various components relative to those lines. We applied the analysis program MPFIT in SPTOOL, and fitted synthetic spectra to the observed spectrum. This program was applied to selected lines individually and derived Fe abundances A(Fe)eff,syn for each line. To generate synthetic spectra, we applied appropriate values of stellar parameters (Teff,syn, log geff,syn, and ξeff,syn).

Determinations of those values are explained later.

Abundance derivation with WIDTH program:

Another analysis program in SPTOOL, WIDTH, calculated abundances based on stellar parameters and the equivalent widths of each line. We set the values of the stellar parameters to be the same as Teff,syn, log geff,syn, and ξeff,syn, assigned appropriate values to the equivalent width (WWIDTH) of each line, and calculated the Fe abundances A(Fe)WIDTH for each line.

Comparison of A(Fe)syn with A(Fe)WIDTH:

In the case of any discrepancy between A(Fe)syn and A(Fe)WIDTH, we re-calculated A(Fe)WIDTH by changing the value of WWIDTH. We considered the WWIDTH value to be the equivalent width of the selected line, if A(Fe)syn was equal to A(Fe)WIDTH.

The values of Teff,syn, log geff,syn, and ξeff,syn were estimated from photometric colors after calibrating the interstellar extinction: (B − V)0 = (B − V) − E(B − V). We adapted an extinction value of 0.04 mag, the average value of the extinction toward the Pleiades cluster (Breger 1986). The effective temperature, Teff,syn, was calculated by using an equation presented by Alonso, Arribas, and Martínez-Roger (1996),

\[
T_{\text{eff}, \text{syn}} = 5040 \left( 0.541 + 0.533(B - V) + 0.007(B - V)^2 \right) + 0.007 \frac{\text{[Fe/H]}}{[\text{Fe/H}]},
\]

where [Fe/H] was assumed to be 0.0 dex. The surface gravity, log geff,syn, was calculated using the equation presented by Gray (1976),

\[
\log g_{\text{syn}} = 4.17 + 0.38(B - V)_0.
\]

Using the obtained Teff,syn and the log geff,syn values, we used the microturbulence velocity equation from Nissen (1981),

\[
\xi_{\text{syn}} = 3.2 \times 10^{-4}(T_{\text{eff}, \text{syn}} - 6390) - 1.3 \times (\log g_{\text{syn}} - 4.16) + 1.7.
\]

3.2. Spectroscopic Analysis of the Stellar Parameters and Metallicity

After deriving the equivalent widths of our selected lines, we re-determined the stellar parameters and metallicity through a spectroscopic analysis. As mentioned above, the WIDTH program derived the Fe abundances from individual Fe I and Fe II. However, the dispersion in the derived abundances from different lines was large if the stellar parameters applied to the WIDTH calculation was inconsistent with the actual values. The stellar parameters were therefore determined to satisfy three criteria simultaneously:

- Excitation equilibrium: the Fe abundances derived from individual Fe I lines have no dependence on the excitation potential — the derived abundance of an
Fe I line is written as
\[ A_1 = a + b \chi, \tag{4} \]
where \( A_1 \) is the abundance derived from the Fe I line; \( \chi \) is the line excitation potential; and \( a \) and \( b \) are the \( y \)-intercept and slope of the regression line, respectively. This criterion was satisfied when \( |b| \) was less than \( 10^{-4} \) (figure 1).

- Ionization equilibrium: the Fe abundances derived from the Fe I lines must be equal to those from the Fe II lines, i.e., the absolute value of the difference between the average of the Fe I abundances \( \langle A_1 \rangle \) and that of the Fe II abundances \( \langle A_2 \rangle \) should be less than 0.001 dex (figure 2).

- Abundances independent of the line strength: the abundances derived from individual Fe I lines are independent of the line strengths—the derived abundances of Fe I lines as a function of equivalent widths are written as
\[ A_1 = p + q W, \tag{5} \]
where \( p \) and \( q \) are the \( y \)-intercept and slope of the regression line, respectively. This criterion was satisfied when \( |q| \) was less than \( 10^{-5} \) (figure 2).

We varied the values of the three stellar parameters \( (T_{\text{eff}}, \log g, \text{and } \xi) \) applied to the WIDTH calculation until the parameter values simultaneously fulfilled these criteria. Once the stellar parameters were determined, we took the average of the Fe abundances derived from the Fe I lines as the stellar Fe abundances. Finally, we subtracted the solar Fe abundance from the stellar abundances, and derived the metallicity of the stars.

Another stellar parameter, the projected rotational velocity \( (v \sin i) \), was derived by spectral synthesis. The method was also used to derive \( v \sin i \) when we applied it to selected Fe lines to measure the abundances. The average and standard deviations of the \( v \sin i \) values derived from the lines were considered to be the rotational velocity and the statistical uncertainty of the velocity, respectively.

To determine statistical uncertainties of the other stellar
where $e_1$ and $e_2$ are the maximum and minimum of the Fe I line excitation potential used in the analysis, and $\sigma_1$ is the standard deviation in the abundance derived from the Fe I lines, and $\Delta(\xi)$ is the standard deviation of the abundance derived from individual Fe I lines with given excitation potentials. The solid line is a regression line, whose slope is less than $10^{-4}$. In such a case, the equilibrium condition is considered to be satisfied.

For the statistical uncertainties in the Fe abundances, we considered two factors: the uncertainty in the accuracy of the atomic data and that in the equivalent width measurements. The former was taken to be the sum of the standard deviation of the abundances derived from the Fe I lines divided by the square root of the number of Fe I lines used. For the latter, the uncertainty was 0.03 dex, corresponding to the error estimate in equivalent width (about 2 mÅ). Including these uncertainties, we calculated the typical uncertainty in the derived metallicity of $\sim 0.05$ dex.

### 3.3. Reliability of Line Selection and the Analytic Method

To estimate the accuracy of our Fe line selection and the analytic method, we derived the stellar parameters and metallicities of stars that have been previously studied: the Sun and HD199960. By applying our method to the Solar Flux Spectrum Atlas (Kurucz et al. 1984), we derived the solar effective temperature, surface gravity, microturbulence velocity, and Fe abundance to be $T_{\text{eff}} = 5720 \pm 25$ K, $g = 4.35 \pm 0.10$ cm s$^{-2}$, $0.90 \pm 0.10$ km s$^{-1}$, and $7.48 \pm 0.04$, respectively. These values were consistent with previously derived values through spectroscopic analyses [e.g., $T_{\text{eff}} = 5718 \pm 25$ K, $g = 4.35 \pm 0.08$ cm s$^{-2}$, $0.86 \pm 0.13$ km s$^{-1}$, $7.48 \pm 0.03$: Takeda et al. (2002), $5779 \pm 23$ K, $4.48 \pm 0.07$ cm s$^{-2}$, $1.04 \pm 0.04$ km s$^{-1}$, $7.47 \pm 0.04$: Santos et al. 2004]. We obtained the spectra of HD 199960 using the SMOKA archive system (Baba et al. 2002) and derived its parameters and metallicity to be $T_{\text{eff}} = 5963 \pm 48$ K, $4.32 \pm 0.11$ cm s$^{-2}$, $1.16 \pm 0.08$ km s$^{-1}$, and $+0.29 \pm 0.04$ dex, respectively. These values were also consistent with previously derived values [e.g., $T_{\text{eff}} = 5924 \pm 10$ K, $4.26 \pm 0.03$ cm s$^{-2}$, $1.13 \pm 0.09$ km s$^{-1}$, $+0.28 \pm 0.02$ dex; Takeda et al. (2005), $5973 \pm 26$ K, $4.39 \pm 0.05$ cm s$^{-2}$, $1.13 \pm 0.03$ km s$^{-1}$, $+0.28 \pm 0.02$ dex; Sousa et al. 2008]. From these analyses, we confirmed the reliability of our selected lines and analytic method.

We also analyzed systematic uncertainties due to instrumental differences. Our sample included HD 470, a Pleiades star whose metallicity was previously measured by Boesgaard and Friel (1990). We obtained its spectrum at both HIDES and GAOES in order to estimate the uncertainties. These results are given in table 3. The stellar parameters derived from the HIDES spectrum were consistent with those from the GAOES spectrum within the statistical uncertainties. Our results agreed with the BF90’s within the errors, although the $\xi$ values differed by $\sim 0.3$ km s$^{-1}$. This difference in $\xi$ caused an uncertainty in [Fe/H] of about 0.05 dex. Because this uncertainty is within the statistical error for [Fe/H], we concluded that the systematic uncertainty due to different instrumentation was negligible.

We could not apply spectral synthesis to HD 3031 due to the rotational velocity, which exceeded 150 km s$^{-1}$, and to HD 697 due to low S/N spectral data. Also, HD 1762 was found to be
Table 3. H II 470 derived stellar parameters.

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<th>$T_{\text{eff}}$ (K)</th>
<th>$\log g$ (cm s$^{-2}$)</th>
<th>$\xi$ (km s$^{-1}$)</th>
<th>(Fe/H) (dex)</th>
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<td>HIDES</td>
<td>6800 ± 114</td>
<td>4.40 ± 0.17</td>
<td>1.95 ± 0.28</td>
<td>+0.07 ± 0.05</td>
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<tr>
<td>GAOES</td>
<td>6875 ± 72</td>
<td>4.50 ± 0.12</td>
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<tr>
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<td>4.38</td>
<td>1.56</td>
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Fig. 3. [Fe/H] of 22 Pleiades stars. The thick dashed line shows the average value of [Fe/H] (+0.03 dex), while the dotted lines indicate 1σ from the average (±0.05 dex)

Fig. 4. [Fe/H] and $v \sin i$ of 22 stars. This plot indicates no correlation between [Fe/H] and $v \sin i$.

Fig. 5. [Fe/H] distribution of 22 Pleiades stars. The stars were divided into 0.05-dex bins around the average [Fe/H], +0.03 dex. The curve represents a Gaussian distribution curve.

4. Results and Discussions

4.1. Metallicity Homogeneity in the Pleiades

We derived the stellar parameters and metallicities of 22 stars in the Pleiades cluster with a precision in metallicity of ±0.05 dex (figure 3 and table 4). The average [Fe/H] of 22 members was +0.03 ± 0.01 dex, with a dispersion of 0.05 dex. We verified the metallicity homogeneity for 22 stars by checking the following three points:

Analysis accuracy: As described in the previous section, we confirmed the reliability of our analysis by deriving the stellar parameters and metallicity of standard stars. No correlation between [Fe/H] with other stellar parameters was a good indicator; for instance, [Fe/H] and $v \sin i$ (figure 4). If a star had a high rotational velocity, the $W_s$ could be overestimated due to blending. Our measurement method of the $W_s$, as described in subsection 3.1, avoided this error, and we found no correlation between [Fe/H] and $v \sin i$.

Dispersion of metallicities: The [Fe/H] dispersion was 0.05 dex, comparable to the metallicity measurement precision (≈0.05 dex). Also, considering the range in the measurement error, the [Fe/H] of all 22 stars fell within 1σ of the average.

Metallicity distribution: The [Fe/H] values of the stars were symmetrically distributed (figure 5).

We also investigated possible correlations between [Fe/H] and other physical properties, such as the spatial positions and the proper motions. Figure 6a shows the spatial positions of the 22 stars. The plot sizes correspond to the metallicities. A comparison of their [Fe/H] with their positions presented no significant feature, such as a clumping of stars with high [Fe/H]. Also, in the case of proper motions (figure 6b), we found no specific correlation with [Fe/H]. These results suggest that the materials in the Pleiades’ parent molecular cloud were uniformly mixed when the members were formed.

4.2. H II 531

One of our targets, H II 531, is also a target of Gebran and Monier (2008, hereafter GM08), who determined the abundances of 18 elements, including Fe, for the 21 A and F Pleiades members. The results of GM08, $T_{\text{eff}} = 7638 ± 125$ K and [Fe/H] = +0.34 ± 0.10 dex, suggest that this object was a late Am-type star, an A star whose spectrum additionally contains very strong metallic lines. However, our result, $T_{\text{eff}} = 7260 ± 128$ K and [Fe/H] = +0.07 ± 0.06 dex, indicates that it is an A9 or F0 star with a [Fe/H] ~ [Fe/H]$_{\text{sun}}$. Both results agree with the spectral classification found in Gray, Napier, and Winkler (2001), A6–F1, which was determined by a line profile analysis of the Ca II K line, hydrogen lines, and metallic lines. However, our H II 531 [Fe/H] differed by 0.27 dex from...
that of GM08. The cause of the difference between our result and that of GM08 may be the use of different lines for the [Fe/H] determination. We determined [Fe/H] by taking the average of [Fe/H] derived from the 45 Fe I lines, and 11 Fe II lines. GM08 used 27 Fe II lines, but no Fe I lines.

4.3. Comparison of Derived Stellar Parameters with Other Methods

In this section we present a comparison of our results of $T_{\text{eff}}$ and log $g$ with those derived by using other methods. We determined $T_{\text{eff}}$ spectroscopically, and set the value against the value derived from photometric methods (Alonso et al. 1996). Figure 7 shows a comparison between our "spectroscopic" $T_{\text{eff}}$ and Alonso’s "photometric" $T_{\text{eff}}$. Two values agree within the errors. Figure 7 also shows that our method could derive effective temperatures of late-type stars with uncertainties ($\Delta T_{\text{eff,spec}} \leq 100$ K) smaller than that derived from the photometric method ($\Delta T_{\text{eff,phot}} \sim 116$ K), but not for early-type stars.

The derived value of log $g$ was compared with evolutionary model estimates. Assuming a Pleiades cluster age of 120 Myr, we adapted the model of Siess et al. (2000: figure 8). The derived log $g$ of all stars agreed well with the model values, except that of BD +21 503. The reason for this inconsistency may be the low S/N ratio of BD +21 503, which meant fewer lines were applied to parameter determinations.
5. Summary

We obtained high-resolution optical spectra of 25 A, F, and G Pleiades stars with the Okayama 1.88-m telescope and HIDES spectrograph and the Gunma 1.5-m telescope and the GAOES spectrograph. The spectral resolution and S/N were 40000 and 70–220, respectively. We determined the stellar parameters of 22 stars, and measured their metallicities with a precision of $\sim 0.05$ dex.

The metallicity average was $+0.03 \pm 0.05$ dex. Because [Fe/H] fell within 1 $\sigma$ of the average, and the [Fe/H] distribution fitted a Gaussian distribution curve, we conclude that the 22 stars possess uniform metallicities. The average metallicity agrees with Wilden et al. (2002) and Boesgaard (2005), indicating a high probability of metallicity homogeneity in the Pleiades. The fact that the measured metallicities of the Pleiades members are close to the solar metallicity suggests that in the Pleiades cluster, no star may possess either significantly high or significantly low metallicity. We found no correlation between the derived [Fe/H] and stellar spatial positions or proper motions, which suggests that the materials in the parent molecular could were uniformly mixed. As a future work, we discuss the abundance uniformity of other elements, such as the $\alpha$ element and Fe-peak elements, and quantitatively analyze the chemical homogeneity in the Pleiades.

This research is based on data collected at Gunma Astronomical Observatory (GAO) and Okayama Astrophysical Observatory (OAO), which is operated by the National Astronomical Observatory of Japan (NAOJ). We thank all of the staff members at both GAO and OAO for their support during the observations. A part of data was collected at Okayama Astrophysical Observatory and obtained from the SMOKA, which is operated by the Astronomy Data Center, National Astronomical Observatory of Japan. This study was supported by “The 21st Century COE Program: The Origin and Evolution of Planetary Systems” of the Ministry of Education, Culture, Sports, Science and Technology. This research made use of the SIMBAD database, operated at CDS, Strasbourg, France.

References

Boesgaard, A. M. 2005, ASP Conf. Ser., 336, 39 (B05)
Kurucz, R. L., Furenlid, I., Brault, J., & Testerman, L. 1984, Solar flux atlas from 296 to 1300 nm (Sunspot, New Mexico: National Solar Observatory)