Stellar Parameters and Chemical Abundances of G Giants

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Abstract

We present basic stellar parameters of 99 late-type G giants based on high-resolution spectra obtained by the High Dispersion Spectrograph attached to Subaru Telescope. These stars are targets of a Doppler survey program searching for extra-solar planets among evolved stars, with a metallicity of $-0.8 < [\text{Fe/H}] < +0.2$. We also derived their abundances of 15 chemical elements, including four $\alpha$-elements (Mg, Si, Ca, Ti), three odd-Z light elements (Al, K, Sc), four iron peak elements (V, Cr, Fe, Ni), and four neutron-capture elements (Y, Ba, La, Eu). Kinematic properties reveal that most of the program stars belong to the thin disk.

Key words: stars: abundances — stars: atmospheres — stars: fundamental parameters — stars: late-type

1. Introduction

Since the first extra-solar planet around the main-sequence star 51 Peg b was discovered in 1995 (Mayor & Queloz 1995), more than 500 planets have been revealed in the solar neighbourhood,\(^1\) providing clues on the planet-formation process around different types of stars. However, only a small fraction of known planet-host stars are of intermediate-mass ($1.5–5 M_\odot$). The properties of planets around these stars are of great importance to constrain planet formation theories (e.g., Ida & Lin 2004). One way to search for extra-solar planets around intermediate-mass stars is monitoring the radial velocities of late-type G, K giants. Their spectra have many sharp absorption lines, and are therefore suitable for obtaining precise radial velocity data by modern Doppler techniques (e.g., Butler et al. 1996).

The East Asian Planets Search Network (EAPSNet, see Izumiura 2005), which was started in 2005, has established an international consortium among Japanese, Korean, and Chinese researchers. More than 500 late-type G, K giants are being monitored with 2-m class telescopes among three countries. Stellar parameters and detailed elemental abundances of some of the targets have been analysed by Takeda, Sato, and Murata (2008) and Liu et al. (2010). As an extension of EAPSNet, the Subaru Planet Search Program started monitoring radial-velocity variations of about 300 late-type G, K giants in 2006. By the end of June 2010, two planets (HD 145457b and HD 180314b) had been discovered in this program (Sato et al. 2010). However, the basic parameters and chemical abundance analysis have not been conducted for this sample.

In this paper we present the first results of stellar parameters and chemical abundances for 99 giants based on high-resolution spectra obtained with Subaru Telescope. In section 2, we describe the observation and data-reduction method. Section 3 gives the derived stellar parameters, including a comparison of different methods. The chemical abundances and kinematic properties are presented in sections 4 and 5, respectively. In the last section, conclusions are presented.

2. Observation and Data Reduction

Targets of Subaru Planet Search Program were selected from Hipparcos Catalogue (ESA 1997) by the following criteria:

1. a colour index of $0.6 \leq B - V \leq 1.0$ and an absolute magnitude of $-3 \leq M_V \leq 2.5$, corresponding to the range of evolved, late-type G giants.
2. a magnitude of $6.5 < V < 7.0$, which enables follow-up observations using 2m-class telescopes.
3. a declination of $\delta > -25^\circ$ so as to be observable in Japan, Korea, and China.

First, each target was observed with the High Dispersion
Spectrograph (HDS: Noguchi et al. 2002) equipped to Subaru Telescope three times with an interval of about 1.5 months, for the purpose of quickly identifying stars with large radial-velocity variations. Then, the most likely candidates with sub-stellar companions were repeatedly observed with the 1.88-m telescope at Okayama Astrophysical Observatory (OAO, Japan), 1.8-m telescope at Bohyunsan Optical Astronomy Observatory (BOAO, Korea), and 2.16-m telescope at Xinglong Station (National Astronomical Observatories, China).

HDS has several setups of gratings, and each has a different spectrum format and wavelength coverage. In the first three runs of this program in 2006, we used StdI2b twice and StdI2a once. The spectra taken with the StdI2a setup with a wavelength coverage of 4900–7600 Å are suitable for chemical abundance analysis. Here, we present the first results of these 99 stars, whose spectra were obtained in 2006 July, with a resolving power of $R \sim 60000$ and a typical signal-to-noise ratio (SNR) of 150–230 pixel$^{-1}$. The bias is determined and subtracted using the over-scan region on CCD, with an IRAF script provided by HDS web page. Then, the reduction of data follows the standard routines. The MIDAS/ECHELLE package is used for order definition, flat-fielding, background subtraction, 1-D spectra extraction, and wavelength calibration. The radial-velocity shift is corrected by fitting the profiles of about 80 pre-selected lines with intermediate strength. Although the Doppler-shift correction is made on the un-normalized spectra, because the spectra lines are narrow (typically $\sim 0.3$ Å), the continuum around such a line could be seen as a constant, and nearly do not affect the measured central wavelength. The uncertainties of the radial-velocity values are about 0.3–0.4 km s$^{-1}$ using this method (see table 8). After that, the one-dimension spectra are normalized by a continuum fit by a cubic spline function with a smooth parameter. The spline interpolation is determined by a set of continuum windows selected from a typical giant spectrum, which usually has a density of 10–15 points per order.

For the purpose of precise radial-velocity measurements, the spectra were taken with an iodine vapor cell inserted into the light path of the spectrograph, and hence the stellar spectral lines located in the wavelength region of 5000–6300 Å were heavily mixed with absorption features in the I$_{2}$ spectrum. We only used the red part of the spectra with wavelengths longer than 6350 Å to analyse the chemical abundances. Equivalent widths were measured by fitting the line profiles with a Gaussian function for the weak lines. While in strong unblended lines, broad damping wings contribute significantly to the equivalent width. The direct integration was used for such kind of lines alternatively.

3. Stellar Parameters

3.1. Effective Temperature

Based on the empirical calibration relations given by Alonso, Arribas, Martínez-Roger (1999, 2001), the effective temperatures ($T_{\text{eff}}$) of our program stars were determined using the $B - V$, $V - K$, and $b - y$ photometric data. The $B - V$ colour indices in Johnson system were obtained by $B - V = 0.850(B_{\text{T}} - V_{\text{T}})$, as described by ESA (1997), where $B_{\text{T}}$ and $V_{\text{T}}$ are Tycho magnitudes in Hipparcos Catalogue. The $K$ magnitudes in $V - K$ were obtained by converting the $K_{s}$ magnitude in Two Micron All Sky Survey (2MASS) to the $K$ magnitude using the calibration relation given by Ramírez and Meléndez (2004), and the $V$ magnitudes were taken from Hipparcos Catalogue. There are 32 stars of our sample that also have $b - y$ data in the catalogue given by Hauck and Mermilliod (1998). As a result, we derived $T_{\text{eff}}$ from $b - y$, besides $V - K$ and $B - V$, and compare the results with those from $B - V$ and $V - K$ in figure 1.

The color excess $E(B - V)_{\lambda}$ was calculated according to Schlegel, Finkbeiner, and Davis (1998), with a slightly revision, described by Arce and Goodman (1999) for those values larger than 0.15 mag. Then, the $E(B - V)$ value for each star was calculated as

\[ E(B - V) = 0.850(B_{\text{T}} - V_{\text{T}}) - E(B - V)_{\lambda} \]

\[ \text{Fig. 1. Comparison of the effective temperatures derived from different colour indices. (a) } T_{\text{eff}} \text{ derived from } B - V \text{ versus that from } b - y. \text{ (b) } T_{\text{eff}} \text{ derived from } V - K \text{ versus that from } b - y. \]
\[ E(B - V) = [1 - \exp(-|D \sin b|/125)] E(B - V)_A, \]  
where \( D \) is the distance of the star and \( b \) is the galactic latitude. Finally, we adopt \( E(V - K) = 2.948 E(B - V) \) as the colour excess for \( V - K \) (Schlegel et al. 1998), and \( E(b - y) = 0.741 E(B - V) \) for \( b - y \) (Crawford & Mandwewala 1976).

The mean difference, \( \langle T_{\text{eff}}(B - V) - T_{\text{eff}}(b - y) \rangle \), is 16 ± 56 K, while the mean difference, \( \langle T_{\text{eff}}(V - K) - T_{\text{eff}}(b - y) \rangle \), is 24 ± 100 K. According to Alonso, Arribas, and Martínez-Roger (1999), the uncertainty of the effective temperature of giants derived from \( V - K \) is estimated to be ± 40 K, which is more accurate than that derived from either \( B - V (\pm 96 \text{ K}) \) or \( b - y (\pm 70 \text{ K}) \). However, most stars in our sample are too bright in the \( K_s \) band (\(< 4.5 \text{ mag}\)) to assure accurate photometry; therefore, the effective temperatures derived from \( V - K \) may not be reliable. Table 1 lists the effective temperatures derived from three different colour indices for the 32 stars.

Another method is the so-called excitation equilibrium method, which forces the derived iron abundances given by different FeI lines to be independent from their excitation potentials of lower states \( \chi_{\text{low}} \). After adjusting the effective temperatures, the slopes on \( \log A - \chi_{\text{low}} \) diagrams for all stars in our sample are smaller than 0.002 dex eV\(^{-1}\), and the mean difference, \( \langle T_{\text{eff}}(\text{eq}) - T_{\text{eff}}(B - V) \rangle \), is 44 ± 117 K. The effective temperatures derived from this method and those from \( B - V \) are compared in figure 2.

### 3.2. Surface Gravity

Surface gravity (\( \log g \)) is determined by

\[
\log g = \log g_\odot + \log \left( \frac{M}{M_\odot} \right) + 4 \log \left( \frac{T_{\text{eff}}}{T_{\text{eff,\odot}}} \right) + 0.4(M_{\text{bol}} - M_{\text{bol,\odot}}),
\]

where \( M \) is the stellar mass, and \( M_{\text{bol}} \) is the bolometric magnitude, defined as

\[
M_{\text{bol}} = V_{\text{mag}} + BC - 5 \log d + 5 + A_V.
\]

Here, \( V_{\text{mag}}, BC, d, \) and \( A_V \) represent the apparent magnitude, bolometric correction, distance, and interstellar extinction, respectively.

The bolometric corrections (\( BC \)) are calculated based on estimated effective temperatures and metallicities, as given in Alonso, Arribas, and Martínez-Roger (1999). The stellar mass is estimated by an interpolation of Yale–Yonsei stellar evolution tracks (Demarque et al. 2004; Yi et al. 2003), which is based on a new convective core overshoot scheme. The Yale–Yonsei evolution tracks can be used for stars from the stage of the pre-main-sequence to the helium-core flash. For a comparison, we also estimated the masses using the evolution tracks of Girardi et al. (2000), in which the helium-core ignition phase is included. By assuming that all the stars correspond to the post-RGB phase, we find that the difference between the two sets of stellar mass is less than 0.3 \( M_\odot \). However, about half of our program stars present an uncertainty of parallax of up to 15\%. According to equations (2) and (3), this will cause an error of \( \sim 0.13 \text{ dex in } \log g \), and about a factor of 1.3 in stellar mass. The interstellar extinctions are adopted by \( A_V = 3.1 E(B - V) \), and Hipparcos parallaxes are used to determine the absolute magnitudes \( (M_V) \).

We also adopt another method that is independent from the parallax data to determine the surface gravities. Since the FeII lines are more sensitive to surface gravities in cool stars...
than Fe I lines, log $g$ can be determined by forcing the abundances of Fe II lines to be the same value as those given by Fe I lines. Despite several uncertainties, such as non-local thermodynamic equilibrium (NLTE) effects and very few Fe II lines, it is still meaningful to compare different sets of log $g$ values. As shown in figure 3, the scatter tends to increase with decreasing surface gravities.

### 3.3. Atomic Data

The log $gf$ values for selected spectral lines are taken from various literature, and listed in table 2. For Fe I lines, we use Oxford oscillator strength data (Blackwell 1982a, 1982b, 1986). For the four heavy elements (Y, Ba, La, Eu), the log $gf$ values are taken from Hannaford (1982), Weise and Martin (1980), Luck and Bond (1991), and Biémont et al. (1982), respectively. For other elements, we use the log $gf$ values given by Chen et al. (2000). Although the atomic data were compiled from different references, it does not affect the results systematically. Moreover, the same program and values of oscillator strength were also adopted by measuring the EWs in Solar Atlas (Kurucz et al. 1984) to determine the solar abundances, so the final results are the differential values relative to the Sun.

### 3.4. Metallicity and Microturbulence Velocity

For most of our program stars, the initial metallicity values were set to [Fe/H] = 0.0. For those stars that have been studied, the initial values were taken from previous literatures (da Silva et al. 2006; Mishenina et al. 2006; Luck & Heiter 2007; Takeda et al. 2008). The abundances of the chemical elements were determined based on the model atmospheres interpolated by a plane–parallel, homogeneous and local thermodynamic equilibrium (LTE) model grid by Kurucz (1993). Chemical abundances were calculated with the ABONTEST8 program supplied by Dr. P. Magain (Liege, Belgium). It calculates the theoretical equivalent widths from the atmospheric model, and matches them with observed values. Several broadening mechanism were taken into account, including natural broadening, thermal broadening, van der Waals damping broadening, and microturbulent broadening. The microturbulence, $\xi_t$, was determined by forcing the iron abundance values given by different Fe I lines to be independent from their EWs, and hence with zero slope on the log $A$–EW diagram. Only those Fe I lines with 10 mÅ < EW < 110 mÅ were used.

### 3.5. Summary

The derived physical parameters of our program stars are summarized in tables 3 and 4. In table 3, effective temperatures were derived from $B - V$, and the surface gravities were derived from Hipparcos parallaxes. However, in table 4 the effective temperatures and surface gravities were derived from the excitation equilibrium and ionization balance, respectively. Although two different sets of stellar parameters are given, we finally adopt those listed in table 3 in the following analysis.

In figure 4, log $L/L_\odot$ versus $T_{\text{eff}}$ is plotted for our program stars with different masses ($1 M_\odot$, $2 M_\odot$, $3 M_\odot$, and $5 M_\odot$) and metallicity ($z = 0.04, 0.02, and 0.01$, corresponding to [Fe/H] = +0.3, 0.0, and −0.3, respectively).
**Table 3.** Physical parameters of program stars.\(^*\)

| HD     | \(T_{\text{eff}}\) (K) | \([\text{Fe/H}]\) | \(\log g\) | \(\xi_t\) (\(\text{km} \, \text{s}^{-1}\)) | \(B - V\) | \(E(B-V)\) | \(M_v\) | \(BC\) | \(M/M_{\odot}\) | \(\log \text{age}\) | \(\log (L/L_{\odot})\) |
|--------|----------------|-----------------|-----------|----------------|--------|---------|--------|--------|--------------|---------------|---------------|
| 100055 | 4900           | −0.16           | 2.780     | 1.79           | 0.929  | 0.008   | 0.720  | −0.296 | 2.29         | 8.90          | 1.77          |
| 101853 | 4834           | −0.21           | 2.549     | 1.76           | 0.955  | 0.019   | 0.098  | −0.322 | 2.58         | 8.75          | 2.00          |
| 103690 | 4730           | −0.32           | 2.499     | 1.61           | 0.996  | 0.010   | 0.560  | −0.366 | 1.70         | 9.24          | 1.84          |
| 105475 | 4764           | −0.10           | 2.638     | 1.46           | 1.007  | 0.016   | 0.345  | −0.351 | 2.74         | 8.69          | 1.94          |

\(^*\) Effective temperatures are derived from \(B - V\) and calibration relation of Alonso, Arribas, and Martínez-Roger (1999). Surface gravities are derived from Hipparcos parallaxes. Complete data is available at (http://pasj.asj.or.jp/v63/n5/630520).

**Table 4.** Atmospheric parameters of program stars.\(^*\)

| HD     | \(T_{\text{eff}}\) (K) | \([\text{Fe/H}]\) | \(\log g\) | \(\xi_t\) (\(\text{km} \, \text{s}^{-1}\)) |
|--------|----------------|-----------------|-----------|----------------|
| 100055 | 5016           | −0.07           | 2.87      | 1.76          |
| 101853 | 4990           | −0.09           | 2.79      | 1.76          |
| 103690 | 4769           | −0.29           | 2.58      | 1.60          |
| 105475 | 4865           | −0.03           | 2.71      | 1.44          |

\(^*\) Effective temperatures are derived from excitation equilibrium method. Surface gravities are derived from ionization balance method. Complete data is available at (http://pasj.asj.or.jp/v63/n5/630520).

**Table 5.** Common stars in this study and other literatures.

| HD     | Literature                          |
|--------|-------------------------------------|
| 145457 | Sato et al. (2010)                  |
| 161502 | Luck and Heiter (2007)              |
| 179799 | da Silva et al. (2006)              |
| 180314 | Sato et al. (2010)                  |
| 185351 | Takeda, Sato, and Murata (2008)     |
| 188993 | Luck and Heiter (2007)              |
| 196134 | Mishenina et al. (2006)             |

It is shown that most of our samples have luminosities \(1.5 < \log L/L_{\odot} < 2.0\), and effective temperatures of \(3.67 < \log T_{\text{eff}} < 3.70\). In figure 5, the derived atmospheric parameters of our stars (filled circles) are compared with those derived by Takeda, Sato, and Murata (2008) (open circles) and Liu et al. (2010) (crosses). The effective temperature \(T_{\text{eff}}\) tends to increase with increasing surface gravity \(\log g\), and the microturbulent velocity \(\xi_t\) tends to decrease with higher surface gravity \(\log g\).

### 3.6. Consistency Check with Literatures

In order to check the consistency of our atmospheric parameters with previous studies, the results are compared with those given by da Silva et al. (2006), Mishenina et al. (2006), Hekker and Meléndez (2007), Luck and Heiter (2007), Takeda, Sato, and Murata (2008), and Sato et al. (2010). All literatures above have determined the parameters of giants based on high resolution spectra. There are totally 7 common stars in our sample with those from the literature, as listed in table 5. Figure 6 compares the effective temperatures, surface gravities, and metallicity of these stars. Our derived temperatures...
are very consistent with others, with $\Delta T_{\text{eff}} \sim 4 \pm 65$ K lower than their values. While the surface gravity difference $\Delta \log g$ is $\sim 0.14 \pm 0.33$ dex lower compared with others’ results, and the metallicity difference $\Delta [\text{Fe}/\text{H}]$ is $\sim 0.09 \pm 0.07$ dex lower than those from the literature.

4. Chemical Abundances

We used the atmospheric parameters listed in Table 3 to derive the [$X$/Fe] ratios of 14 elements (Al, Ba, Ca, Cr, Eu, K, La, Mg, Ni, Sc, Si, Ti, V, and Y). Those trends are plotted in Figure 9 to Figure 13 (filled circles), together with the trends from Takeda, Sato, and Murata (2008, open circles) as a comparison. The measured equivalent widths of the selected lines of our program stars are listed in Table 9, which is only available in the electronic form.$^3$

4.1. Error Analysis

The uncertainties in the chemical abundances were estimated by changing the atmospheric parameters in a reasonable range. Table 6 gives the abundance differences due to deviations of the effective temperature of 100 K, the surface gravity of 0.15 dex, the iron abundance of 0.1 dex, and the microturbulent velocity of 0.1 km s$^{-1}$. For most of the chemical elements, the uncertainties are less than 0.1 dex, except for Ti and V. The uncertainties of these two elements can be as high as 0.15 dex.

Another source of uncertainties is the error of the equivalent widths caused by a mixture of the intrinsic stellar lines and the I$_2$ lines, since the spectra of our program stars are I$_2$-superposed for precise radial-velocity measurements. To check the uncertainties caused by iodine lines, we used the pure stellar spectra of HD 145457 taken in OAO to measure the equivalent widths, and to determine the chemical abundances.

In Doppler surveys, spectra of fast-rotation B-type stars are often obtained with an I$_2$ cell to deconvolute instrumental profiles (IPs, e.g., Butler et al. 1996). The spectra of such stars are featureless, and thus provide a simple way to check how the stellar spectra are contaminated by I$_2$ absorption lines at different wavelengths in this study. The I$_2$-superposed spectra of a B star (HR 5685, B8V), I$_2$-superposed spectra of HD 145457, and the pure spectra of HD 145457 around 6400 Å and 6700 Å are plotted in Figure 7. Around 6400 Å, the integrated equivalent width of I$_2$ lines is about 6 mA/Å, which causes an uncertainty of equivalent width of about 3–4 mA for a typical spectral line in our I$_2$-superposed spectrum in this region. However, around 6700 Å, the integrated equivalent width of I$_2$ lines is about 4 mA/Å, 30% smaller than that around 6400 Å. The uncertainty of equivalent width caused by I$_2$ lines is estimated to be 2 mA.

Furthermore, we measured the equivalent widths using the I$_2$-superposed spectrum and pure spectrum of HD 145457. The spectral lines were separated into three groups, with wavelengths of $\lambda < 6500$ Å, $6500$ Å $< \lambda < 7000$ Å, and $\lambda > 7000$ Å, respectively. The results are compared in Figure 8. We find that the mean differences ($EW_{I_2} - EW_{\text{pure}}$) of three groups are $-0.05 \pm 5.22$ mA, $-0.33 \pm 4.33$ mA, and $+1.48 \pm 6.38$ mA, which infers that our EW values are not significantly influenced

$^3$ [http://pasj.asj.or.jp/v63/n5/630520/].
Table 6. Estimated errors for abundances of a typical late-type giant HD109305, with $T_{\text{eff}} = 4663$ K, log $g = 2.44$, [Fe/H] = −0.30, and $\xi_t = 1.77$ km s$^{-1}$, taken from table 3.

|            | $\Delta [X/H]$ | $\Delta T_{\text{eff}}$ | $\Delta \log g$ | $\Delta [\text{Fe/H}]$ | $\Delta \xi_t$ | $\sigma_{\text{Total}}$ |
|------------|----------------|--------------------------|-----------------|------------------------|----------------|--------------------------|
| [Fe/H]     | 0.06           | 0.01                     | 0.01            | −0.02                  | 0.06           |                          |
| [FeII/H]   | −0.07          | 0.08                     | 0.04            | −0.02                  | 0.12           |                          |
| [Mg/H]     | 0.05           | −0.01                    | 0.01            | −0.01                  | 0.05           |                          |
| [Al/H]     | 0.07           | −0.01                    | 0.00            | −0.02                  | 0.07           |                          |
| [Si/H]     | −0.02          | 0.03                     | 0.02            | −0.01                  | 0.04           |                          |
| [Ca/H]     | 0.10           | −0.01                    | 0.00            | −0.04                  | 0.11           |                          |
| [Sc/H]     | −0.01          | 0.06                     | 0.03            | −0.03                  | 0.07           |                          |
| [Ti/H]     | 0.15           | 0.00                     | −0.01           | −0.03                  | 0.15           |                          |
| [V/H]      | 0.15           | 0.00                     | 0.00            | −0.01                  | 0.15           |                          |
| [Cr/H]     | 0.09           | 0.00                     | 0.00            | −0.03                  | 0.09           |                          |
| [Ni/H]     | 0.05           | 0.03                     | 0.02            | −0.02                  | 0.06           |                          |
| [Y/H]      | −0.01          | 0.07                     | 0.04            | 0.00                   | 0.08           |                          |
| [Ba/H]     | 0.02           | 0.02                     | 0.06            | −0.05                  | 0.08           |                          |
| [La/H]     | 0.02           | 0.07                     | 0.04            | −0.01                  | 0.08           |                          |
| [Eu/H]     | −0.01          | 0.07                     | 0.04            | −0.01                  | 0.08           |                          |
| [K/H]      | 0.10           | −0.04                    | 0.01            | −0.05                  | 0.12           |                          |

Fig. 7. Comparison of the I$_2$-superposed spectrum (taken in Subaru) and the pure spectrum (taken in OAO) for HD 145457 around 6400 Å and 6700 Å. The calculated RMS residuals are 1.2% around 6400 Å and 0.7% around 6700 Å. Two portions of I$_2$-superposed spectrum for a fast rotation, B-type star (HR 5685, taken in Subaru) are also plotted in the upper panel.

Fig. 8. Comparison of equivalent widths (EWs) measured using I$_2$-superposed spectra taken in Subaru (X axis) and pure spectra taken in OAO (Y axis). The spectral lines are separated into three groups according to their wavelengths. The filled circles are 12 lines with wavelengths $\lambda < 6500$ Å. The open circles are 44 lines with wavelengths 6500 Å < $\lambda < 7000$ Å. The crosses are 31 lines with wavelengths $\lambda > 7000$ Å. The mean differences $\langle EW_{\text{pure}} - EW_{\text{I2}} \rangle$ are $-0.05 \pm 5.22$ mÅ, $-0.33 \pm 4.33$ mÅ, and $+1.48 \pm 6.38$ mÅ, respectively.

by the I$_2$ absorption lines. The chemical abundances determined by pure stellar spectra are compared with our results using Subaru spectra in table 7. It is shown that the uncertainties of the chemical abundances caused by a mixture of I$_2$ lines range from 0.02 to 0.09 dex, which are smaller than the uncertainties caused by errors of the atmospheric parameters. Therefore, we concluded that the weak I$_2$ absorption lines in
the red part of our spectra nearly do not affect the chemical abundance measurements.

4.2. \(\alpha\)-Elements (Mg, Si, Ca, Ti)

The \(\alpha\)-elements are mainly produced in SNe II nucleosynthesis (Woosley & Weaver 1995), and show enhancements in metal-poor stars. In figure 9, we plot \([X/\text{Fe}]\) ratios of Mg, Si, Ca, and Ti against \([\text{Fe}/H]\), together with trends taken from Takeda, Sato, and Murata (2008). Except for the trend of \([\text{Ti}/\text{Fe}]\) against \([\text{Fe}/H]\) with a large scatter, three of the other \(\alpha\)-elements exhibit enhancement towards lower metallicity. However, their decreasing trends with increasing metallicity are slightly different. Both the \([\text{Mg}/\text{Fe}]\) and \([\text{Ca}/\text{Fe}]\) show a turn-off trend towards a flat pattern at \([\text{Fe}/H] \approx -0.2\), which is in good agreement with previous studies on both giants (Takeda et al. 2008; Liu et al. 2007) and dwarfs (Chen et al. 2000), while the \([\text{Mg}/\text{Fe}]\) turns to decrease at \([\text{Fe}/H] > 0\). Despite an increasing trend with decreasing metallicity for \([\text{Fe}/H] < -0.4\), \([\text{Si}/\text{Fe}]\) shows a larger scatter for higher metallicity, leaving the flat pattern shown in Takeda, Sato, and Murata (2008) (open circles in figure 9) unclear. Oxygen is another important \(\alpha\) element for giants. But in our spectra, the [O I] forbidden lines at 6300 Å are not covered by the CCD, and the lines at 6363 Å are very weak and close to the edge. To make sure that our results are reliable, the oxygen abundance is not included in this study.

4.3. Odd-Z Light Elements (Al, K, Sc)

As shown in figure 10, \([\text{Al}/\text{Fe}]\) shows a decreasing trend with increasing metallicity for \([\text{Fe}/H] < -0.2\), and a solar pattern towards higher metallicity. Our results are consistent with Liu et al. (2007). Chen et al. (2000) found a rather steep upturn of \([\text{Al}/\text{Fe}]\) at \([\text{Fe}/H] = -0.2\) in a sample of dwarfs. However, in our results the upturn is rather smooth. \([\text{K}/\text{Fe}]\) exhibits a larger dispersion, because only very few numbers of lines are available. The trend of \([\text{Sc}/\text{Fe}]\) is similar to that of \([\text{Ti}/\text{Fe}]\), with both of them showing a flat pattern when data with larger dispersion are excluded. This result is also consistent with Takeda, Sato, and Murata (2008).

4.4. Iron-Peak Elements (V, Cr, Ni)

The iron-peak elements are believed to be mainly produced in SNe Ia, and should have the same abundance patterns with iron. In figure 11, we plot \([X/\text{Fe}]\) versus \([\text{Fe}/H]\) for three iron-peak elements (V, Cr, and Ni). \([V/\text{Fe}]\) shows an increasing trend with increasing metallicity, which is contrast to Takeda’s results (plotted as open circles in the same figure). The hyperfine structure (HFS) effect has been considered in our work. The adopted HFS data is taken from Kurucz.\(^4\) Liu et al. (2007) suggests the HFS effect can lead to a correction as large as 0.5 dex for vanadium abundance in giants. However, we find that the corrections due to introduction of HFS effect are

\(^{4}\) (http://kurucz.harvard.edu/linelists.html).

Table 7. Comparison of chemical abundances of HD 145457.

| \(\Delta[X/\text{H}]\) | \([X/\text{H}]_2 - [X/\text{H}]_{\text{pure}}\) |
|--------------------|------------------|
| \(\Delta[\text{Fe}/\text{H}]\) | 0.02 |
| \(\Delta[\text{FeII}/\text{H}]\) | 0.04 |
| \(\Delta[\text{Mg}/\text{H}]\) | 0.04 |
| \(\Delta[\text{Al}/\text{H}]\) | 0.03 |
| \(\Delta[\text{Si}/\text{H}]\) | 0.04 |
| \(\Delta[\text{Ca}/\text{H}]\) | 0.09 |
| \(\Delta[\text{Ti}/\text{H}]\) | 0.04 |
| \(\Delta[\text{V}/\text{H}]\) | 0.02 |
| \(\Delta[\text{Cr}/\text{H}]\) | 0.07 |
| \(\Delta[\text{Ni}/\text{H}]\) | 0.07 |
| \(\Delta[\text{Y}/\text{H}]\) | 0.02 |
| \(\Delta[\text{Ba}/\text{H}]\) | 0.02 |
| \(\Delta[\text{La}/\text{H}]\) | 0.03 |
| \(\Delta[\text{Eu}/\text{H}]\) | 0.02 |
| \(\Delta[\text{K}/\text{H}]\) | … |

* Determined by pure stellar spectra taken in OAO, and \(I_2\) superposed spectra taken in Subaru.
between −0.002 dex and 0.012 dex, and can be neglected (see figure 12). The discrepancy is due to the difference of HFS effect from line to line, and the vandium lines we used in this work are different from those in Liu et al. (2007).

The [Cr/Fe] trend in our sample is consistent with Takeda’s, except for a few stars with higher [Cr/Fe] values. For these stars, the relation of [Ni/Fe] vs. [Fe/H] keeps the solar pattern in the range of −0.8 < [Fe/H] < −0.1, while showing an overabundance for higher metallicity, and hence systematically higher than Takeda’s result. A possible upturn at [Fe/H] ~ 0.0 has also been found in both giants (e.g., Liu et al. 2007) and dwarfs (e.g., Edvardsson et al. 1993).

4.5. Heavy Elements (Y, Ba, La, Eu)

Those elements heavier than iron are mainly produced via the neutron-capture process. Two major mechanisms are generally considered: the r-process and the s-process, corresponding to neutron-rich and neutron-poor environments, respectively. In our analysis, one r-process element (Eu), one light s-process element (Y) and two heavy s-process elements (Ba, La) are included. Their abundances trend against [Fe/H] are plotted in figure 13.

Despite a large scatter, as often observed in field stars, the ratio of [La/Eu], [La/Y], and [La/Ba] may provide important information of the Galactic chemical evolution history. As a typical r-process element, europium is mainly produced in core-collapse supernovae (SNe) with masses $8 M_\odot < M < 10 M_\odot$ and the pattern still remains uncertain. Previous work (Simmerer et al. 2004) of La and Eu revealed that the s-process may be active as early as [Fe/H] = −2.6. In figure 14, [La/Eu], [La/Y], and [La/Ba] are plotted as functions of [Fe/H] (from top to bottom). From our plot, a decline of [La/Eu], although not very clear, can be seen in lower metallicity down to −0.7.

In the convection zone of low-mass AGB stars, where slow neutron-capture reactions take place, the neutron flux per seed nuclei is inversely proportional to the density of the iron-peak nucleus. The metal-poor stars produce light s-process
elements (such as Y) more efficiently than the heavy s-process elements (such as Ba, La). The [La/Y] versus [Fe/H] in the middle panel of figure 14 shows marginal increasing trend with decreasing metallicity, consistent with the theoretical prediction (e.g., Busso et al. 1999). [La/Ba] shows a flat trend with [Fe/H] in the bottom panel of figure 14. This is consistent with the theoretical prediction that they are produced through the same producing mechanism.

5. Kinetics Parameters

We derived the kinetics parameters \((U_{\text{LSR}}, V_{\text{LSR}}, W_{\text{LSR}})\) based on method given by Johnson and Soderblom (1987). The radial velocities \((RV_{\text{helio}})\) were measured based on our spectra, and corrected to heliocentric velocities. The positions, parallaxes, and proper motions were taken from Hipparcos data. By adopting a solar motion of \((U, V, W)_\odot = (-10.00 \pm 0.36, +5.25 \pm 0.62, +7.17 \pm 0.38)\) in \(\text{km s}^{-1}\), given by Dehnen and Binney (1998), the Galactic velocity components \(U, V,\) and \(W\) of our program stars were corrected to the local standard of rest (LSR). It is hard to clarify whether a star in
the solar neighborhood belongs to a thin disk or a thick disk. We applied the kinematic method proposed by Bensby, Feltzing, and Lundström (2003) to calculate the relative probability for the thick-disk-to-thin-disk (TD/D) membership. In Bensby, Feltzing, and Lundström (2003), thin-disk and thick-disk stars are thought to follow Gaussian distributions in Galactic velocity space (\(U, V, W\)). By assuming different asymmetric velocity drifts and dispersions, the relative probability of belonging to different populations can be calculated. For instance, a star with TD/D = 10 means that it is 10-times more likely to belong to a thick disk than to a thin disk. In our sample, one star (HD 115903) with TD/D > 10.0 and two stars (HD 138425 and HD 176973) with 1.0 < TD/D < 10.0 are more likely to be a thick-disk star rather than a thin-disk star. Those stars are plotted as open circles on Toomre diagram in figure 15, and listed with a mark ‘TD’ in the last column of table 8, as well as their kinetics parameters mentioned above.

6. Conclusion

In this work we determine the atmospheric parameters, kinematic properties and chemical abundances of 99 late-type giants based on high resolution spectra obtained in Subaru Planet Search Program, covering the metallicity range −0.8 < [Fe/H] < +0.2. We obtained two sets of stellar parameters derived from different methods. The photospheric chemical abundances of 15 elements, including four \(\alpha\)-elements (Mg, Si, Ca, Ti), three odd-Z light elements (Al, K, Sc), four iron peak elements (V, Cr, Fe, Ni), and four neutron-capture elements (Y, Ba, La, Eu) were determined. The kinematic parameters were calculated, and most of our sample are thin disk stars. From the results of abundances, we conclude that the abundance ratios, [Mg/Fe] and [Ca/Fe], show an increasing trend with decreasing metallicity for −0.8 < [Fe/H] < −0.2, while they flatten out towards higher metallicity. A decreasing trend of [Mg/Fe] with increasing metallicity is detected for giants at [Fe/H] > 0. The upturn of [Al/Fe] versus [Fe/H] at [Fe/H] = −0.2 in giants is not as steep as that in dwarfs (e.g., Chen et al. 2000). The [Ni/Fe] versus [Fe/H] shows an upturn at [Fe/H] = 0.0 and an overabundance towards higher metallicity. The [La/Y] ratio shows an increasing trend with decreasing metallicity, which is consistent with the prediction of AGB nucleosynthesis.

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Table 8. Kinetics parameters of program stars.*

| HD   | \(RV_{\text{helio}}\) (km s\(^{-1}\)) | \(U_{\text{LSR}}\) (km s\(^{-1}\)) | \(V_{\text{LSR}}\) (km s\(^{-1}\)) | \(W_{\text{LSR}}\) (km s\(^{-1}\)) | TD/D |
|------|---------------------------------|-------------------------------|-------------------------------|-------------------------------|------|
| 100055 | 6.69 ± 0.37                     | 2.9 ± 1.3                     | −15.4 ± 2.6                   | 13.5 ± 0.7                    | 0.01 |
| 101853 | 2.81 ± 0.36                     | −30.9 ± 3.4                   | 6.7 ± 0.7                     | 17.3 ± 1.3                    | 0.01 |
| 103690 | −19.28 ± 0.35                   | −58.6 ± 3.8                   | 5.0 ± 1.1                     | 8.9 ± 1.7                     | 0.02 |
| 105475 | 0.35 ± 0.35                     | −80.9 ± 11.8                  | −0.4 ± 1.3                    | 16.9 ± 1.7                    | 0.06 |

* Complete data is available at [http://pasj.asj.or.jp/v63/n5/630520](http://pasj.asj.or.jp/v63/n5/630520).
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