ABUNDANCES OF REFRACTORY ELEMENTS FOR G-TYPE STARS WITH EXTRASOLAR PLANETS

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ABSTRACT

We confirm the difference in chemical abundance between stars with and without exoplanets and present the relation between chemical abundances and physical properties of exoplanets, such as planetary mass and the semimajor axis of planetary orbit. We obtained the spectra of 52 G-type stars from the Bohyunsan Optical Astronomy Observatory (BOAO) Echelle Spectrograph and carried out abundance analyses for 12 elements: Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Co, and Ni. We first found that the [Mn/Fe] ratios of planet-host stars are higher than those of comparison stars over the entire metallicity range, and we then found that in metal-poor stars of [Fe/H] < -0.4 the abundance difference was larger than in metal-rich samples, especially for the elements of Mg, Al, Sc, Ti, V, and Co. After examining the relation between planet properties and metallicities of planet-host stars, we observed that planet-host stars with low metallicities tend to have several low-mass planets ($<M_J$) instead of a massive gas-giant planet.

Key words: planetary systems - stars: abundances - stars: fundamental parameters

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Since the first discovery of an exoplanet around a normal star, 51 Peg b (Mayor & Queloz 1995), more than 500 exoplanets have been discovered. From sufficient samples of planetary systems, abundance studies of planet-host stars (PHSs) have investigated the differences in elemental abundances between stars with and without exoplanets. At first, Gonzalez (1998) suggested, after a spectral analysis of eight PHSs, that PHSs tend to be metal-rich, and other studies confirmed that PHSs are metal-rich relative to normal-field stars in the solar neighborhood (Gonzalez et al. 2001; Santos et al. 2001, 2003, 2004, 2005; Bodaghee et al. 2003; Laws et al. 2003; Bond et al. 2006; Ecuvillon et al. 2007; Sousa et al. 2008). The studies using a large number of samples revealed that the probability of finding an exoplanet exponentially increased with increasing metallicity (Fischer & Valenti 2005; Johnson et al. 2010). Despite efforts to find the abundance differences for every element other than iron, however, most studies found no systematic difference in abundance of α -elements between stars with and without exoplanets, except some studies (Bodaghee et al. 2003; Gilli et al. 2006; Robinson et al. 2006) that suggested potential differences between PHSs and comparison stars for some elements (e.g., Mg, Al, Si, Mn, V, Co, and Ni).

In most elemental abundance studies, however, the samples were simply divided into two groups of stars: those with and without exoplanets. Most stars without known exoplanets have not been thoroughly examined for a sufficient period. Even if the stars had been observed for long periods of time, it still would be possible that those stars have several planets whose masses fall below the observational limit. Considering this incompleteness of samples with and without exoplanets, the statistical differences in chemical abundance between two groups of stars (those with planets and without known planets) would have limited reliability.

Nevertheless, it is worthwhile to investigate the relation between chemical abundance in the host star and planetary properties in the samples of planet hosts. The number of lowmass exoplanets, such as Neptunian planets, is continuously increasing with more precise observation (Melo et al. 2007; Rivera et al. 2005; McArthur et al. 2004; Vogt et al. 2005). Because the exoplanets have a wide range of mass, it is possible to examine the relation between planetary mass and chemical abundance in the host star. In this respect, Sousa et al. (2008) suggested that the detectability of Neptune-class planets may become higher in stars with low metallicities. This implies that low-mass planets may be formed differently from massive gasgiant planets, and that there is a relation between planetary mass and the metallicity of the host star.

On the other hand, in the core-accretion scenario of planet formation, the amount of metals is important to the formation of not only terrestrial planets but also gas-giant planets, which require a lot of planetesimals for their core formation. The relation between the metallicities of host stars and planet detectability was presented in the abundance studies of the uniform samples (Santos et al. 2004, 2005; Fischer & Valenti 2005; Sousa et al. 2008; Johnson et al. 2010) and supported by a theoretical study using the core-accretion model (Ida & Lin 2004). But there are many other elements involved in the process of planet formation. For example, the elements Mg, Al, Si, Ca, and Ni are fairly abundant in the solar system relative to the amount of iron, which represents the metallicity of planetary systems. Mg, Al, Si, and Ca are major elements in the condensation process at high temperatures (Lodders 2003) and show different ratios of [X/H] from metallicity ([Fe/H]) in low-metallicity stars via the Galactic chemical evolution. Therefore, it is likely that these elements are involved in the process of planet formation, and it is useful to investigate the relation between planets and abundances in their host stars with low metallicities.

As mentioned above, because of limits of the detection and observing time, what we call stars without planets are merely those with no massive planets with a short orbital period. Hence, we focused on the samples of PHSs and properties of their planets that have been well-confirmed already, for example, hot Jupiters. In addition, if certain elements helped form planets their effects would be easily observed in metal-poor

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Figure 1. Sample list including planet information. The size of circles represents planet mass $(M_J \sin i)^{1/3}$, which is the relative size if all planets have the same density. The red circles indicate the planets in multiple planetary systems. (A color version of this figure is available in the online journal.)

stars because the insufficiency of metals provided the poor conditions for forming planets according to the core-accretion scenario. The chemical abundances of α -elements such as Mg, Al, Si, and Ca are more enhanced relative to the metallicity of low-metallicity stars. It is possible, therefore, that a detailed abundance analysis of low-metallicity stars can provide a clue to the condensation process in planetesimal formation.

To achieve the goal of this study, we present the abundances of 12 elements: Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Co, and Ni, for PHSs and stars without known exoplanets that are within 20 pc from the Sun, as well as the relation between the abundances of host stars and the properties of their planets. In Section 2 we introduce the samples and observations and in Section 3 we present the abundances of host stars with the properties of planets around those host stars, and in Section 5 we discuss the differences in abundance results and evaluate the probability that the abundances of the two groups have the same distribution using statistical testing.

2. THE DATA

2.1. Samples

The G-type stars among PHSs were gathered from several exoplanet references (e.g., Butler et al. 2006; Jean 2009). Some controversial objects (HD 24040, HD 33636, and HD 137510) are excluded from the list of PHSs and regarded as comparison targets. We constrained the PHS samples to the G-type stars with $\delta > -10^{\circ}$ and V < 9.0 to create conditions that can be observable and bright enough to obtain high signal-to-noise (S/N) spectra with the 1.8 m telescope at the Bohyunsan Optical Astronomy Observatory (BOAO). The comparison stars with no known planets were adopted from The *Tycho-2* Spectral Type Catalog (Wright et al. 2003). These comparison stars also have $\delta > -10^{\circ}$ and V < 9.0 in the solar-neighborhood G-type stars within 20 pc from the Sun. For this abundance study, we present

the results of 34 PHSs and 18 comparison stars in the list of G-type stars.

2.2. Observations and Data Reduction

The observations were carried out with the 1.8 m telescope at BOAO in 2008 and 2009. All spectra were obtained from the BOAO Echelle Spectrograph (BOES) using 200 or 300 μ m fiber. The observed spectra have a spectral resolution of R either about 30,000 (using 300 μ m fiber) or 45,000 (using 200 μ m fiber), and S/Ns higher than 150 at 6070 Å. The wavelength range of the spectra is from 3800 Å to 8800 Å, covering the full optical region. The observational log and basic data for 52 targets are listed in Table 1. In this table, Columns 2-4 show the observation date, exposure time (s), and S/N at 6070 Å. Column 5 shows the radial velocity that was estimated by the difference between the observed and rest-frame wavelengths of spectral lines in this study. Columns 6–9 represent the stellar parameters determined by fine analysis, which is explained in Section 3. Column 10 indicates the spectral types of samples adopted from SIMBAD.

Among the 52 observed G-type stars, 34 stars were found to have planets around them via the radial-velocity method, and the semimajor axes and masses of their planets are shown in Figure 1, which also includes 18 comparison samples. Since we are focusing on the relation between chemical abundances of host stars and properties of their planets, the observed samples of PHSs outnumbered comparison stars. In Figure 1, the circle size represents the mass as $(M_J \sin i)^{1/3}$, which is the relative size when all planets have the same density, and the *x*-axis indicates the semimajor axis of a planet. There are 48 planets in these 34 PHSs, and 10 planets are less massive than 10 M_{Nep} (the mass of Neptune is 0.054 M_J); only one planet, HD 190360, is as massive as 1 M_{Nep} .

The reduction of observed spectra was carried out with the IRAF echelle package to produce spectra for each order of the echelle spectrum. The echelle aperture tracing was performed

Table 1 Target List

Star	Date	Exposure (s)	S/N	RV^a $(km s^{-1})$	T _{eff} (K)	log g (dex)	[Fe/H] (dex)	$\frac{\xi_t}{(kms^{-1})}$	Type ^b
34 Planet-hos	t Stars								
HD 10697	2008 Dec 18	3600	400	-46.0 ± 0.5	5662 ± 80	4.07 ± 0.11	$+0.17 \pm 0.05$	0.94 ± 0.07	G5IV
HD 16141	2008 Dec 19	4800	450	-51.0 ± 0.5	5755 ± 83	4.17 ± 0.11	$+0.14 \pm 0.06$	0.96 ± 0.09	G5IV
HD 16400	2008 Dec 19	2400	500	9.1 ± 0.5	4951 ± 91	2.95 ± 0.11	$+0.12 \pm 0.05$	1.34 ± 0.09	G5III:
HD 17156	2009 Feb 6	4500	200	-3.2 ± 0.4	6079 ± 98	4.24 ± 0.11	$+0.21 \pm 0.06$	1.06 ± 0.10	G5
BD+20 518	2009 Feb 7	4800	250	-5.3 ± 0.3	5540 ± 83	4.31 ± 0.10	$+0.30 \pm 0.07$	0.73 ± 0.08	G5
HD 20367	2008 Dec 19	3600	500	6.5 ± 0.3	6253 ± 103	4.62 ± 0.12	$+0.16 \pm 0.06$	1.25 ± 0.08	G0
HD 28305	2008 Dec 18	360	450	38.4 ± 0.3	4949 ± 84	2.85 ± 0.11	$+0.21 \pm 0.08$	1.42 ± 0.09	G9.5III
HD 37124	2009 Feb 8	3600	250	-23.0 ± 0.3	5551 ± 79	4.48 ± 0.11	-0.43 ± 0.06	0.72 ± 0.09	G4IV-V
HD 38529	2008 Dec 18	3600	350	30.4 ± 0.2	5574 ± 74	3.76 ± 0.10	$+0.32 \pm 0.09$	1.26 ± 0.10	G4V
HD 43691	2009 Feb 9	3600	200	-28.7 ± 0.4	6229 ± 101	4.25 ± 0.11	$+0.28 \pm 0.07$	1.29 ± 0.09	G0
HD 45350	2009 Feb 9	3600	200	-20.6 ± 0.3	5636 ± 84	4.37 ± 0.10	$+0.33 \pm 0.06$	0.95 ± 0.09	G5
HD 52265	2008 Dec 18	3600	450	54.1 ± 0.3	6217 ± 103	4.35 ± 0.11	$+0.24 \pm 0.06$	1.16 ± 0.11	G0V
HD 74156	2009 Feb 4	4500	300	3.7 ± 0.4	6097 ± 97	4.28 ± 0.12	$+0.13 \pm 0.06$	1.10 ± 0.11	G0
HD 75732	2008 Apr 27	1200	200	27.5 ± 0.2	5246 ± 80	4.26 ± 0.09	$+0.35\pm0.08$	0.89 ± 0.07	G8V
HD 75898	2009 Feb 9	4500	250	21.9 ± 0.4	6063 ± 93	4.19 ± 0.11	$+0.23 \pm 0.06$	1.13 ± 0.12	G0
HD 81040	2008 Apr 28	3600	250	49.2 ± 0.3	5795 ± 87	4.71 ± 0.11	-0.04 ± 0.07	0.80 ± 0.08	G0V
HD 88133	2009 Feb 6	3600	250	-3.3 ± 0.3	5414 ± 80	4.03 ± 0.10	$+0.37\pm0.07$	0.88 ± 0.08	G5IV
HD 89307	2008 Apr 27	2700	200	23.0 ± 0.3	6003 ± 94	4.55 ± 0.12	-0.11 ± 0.06	1.08 ± 0.11	G0V
HD 92788	2009 Feb 4	3600	350	-4.6 ± 0.3	5751 ± 88	4.38 ± 0.10	$+0.31\pm0.07$	0.94 ± 0.09	G5
HD 95128	2008 Apr 27	600	300	11.0 ± 0.3	5900 ± 89	4.36 ± 0.11	$+0.03\pm0.06$	1.14 ± 0.09	G1V
HD 104985	2008 Apr 24	900	250	-20.1 ± 0.3	4623 ± 70	2.27 ± 0.12	-0.38 ± 0.07	1.43 ± 0.10	G9III
HD 106252	2008 Apr 28	3600	250	15.5 ± 0.3	5976 ± 92	4.56 ± 0.12	-0.02 ± 0.05	0.93 ± 0.09	G0
HD 117176	2008 Apr 24	600	300	5.2 ± 0.2	5520 ± 74	4.00 ± 0.11	-0.07 ± 0.05	0.94 ± 0.08	G5V
HD 143761	2008 Apr 27	600	300	17.7 ± 0.3	5817 ± 84	4.30 ± 0.12	-0.21 ± 0.06	0.91 ± 0.08	G0Va
HD 149026	2009 Feb 4	4800	250	-17.9 ± 0.5	6194 ± 101	4.39 ± 0.11	$+0.32 \pm 0.07$	1.16 ± 0.10	G0IV
HD 154345	2008 Apr 24	1200	200	-46.6 ± 0.3	5452 ± 80	4.54 ± 0.10	-0.08 ± 0.05	0.46 ± 0.10	G8V
HD 155358	2008 Apr 28	3000	250	-9.2 ± 0.4	5944 ± 91	4.27 ± 0.13	-0.63 ± 0.07	1.06 ± 0.08	G0
HD 185269	2008 Apr 24	2400	250	1.3 ± 0.3	6047 ± 94	4.04 ± 0.12	$+0.14 \pm 0.07$	1.28 ± 0.11	G0IV
HD 186427	2008 Apr 24	1800	300	-27.4 ± 0.3	5780 ± 88	4.44 ± 0.11	$+0.09\pm0.06$	0.95 ± 0.09	G3V
HD 190228	2008 Apr 28	3000	200	-50.1 ± 0.3	5278 ± 68	3.78 ± 0.11	-0.30 ± 0.06	1.06 ± 0.10	G5IV
HD 190360	2008 Apr 24	1200	250	-44.7 ± 0.3	5533 ± 81	4.31 ± 0.10	$+0.22 \pm 0.07$	0.82 ± 0.09	G6IV+
HD 195019	2008 Apr 28	2400	350	-91.4 ± 0.3	5820 ± 86	4.19 ± 0.11	$+0.06 \pm 0.06$	1.06 ± 0.09	G3IV-V
HD 209458	2008 Dec 19	3600	300	-14.7 ± 0.3	6127 ± 101	4.43 ± 0.12	$+0.02 \pm 0.06$	1.16 ± 0.12	G0V
HD 217014	2008 Dec 18	1800	500	-33.1 ± 0.2	5830 ± 87	4.50 ± 0.11	$+0.24 \pm 0.05$	1.05 ± 0.09	G2.5IVa
18 Compariso	on Stars								
HD 10307	2008 Dec 18	1800	450	4.4 ± 0.2	5940 ± 91	4.42 ± 0.11	$+0.05\pm0.05$	1.14 ± 0.09	G1.5V
HD 13974	2009 Feb 9	360	250	3.6 ± 0.8	5944 ± 92	4.43 ± 0.12	-0.43 ± 0.06	0.33 ± 0.26	G0.5V
HD 24040	2009 Feb 8	3600	250	-9.3 ± 0.3	5915 ± 89	4.41 ± 0.11	$+0.24\pm0.10$	0.98 ± 0.09	G0
HD 26722	2008 Dec 18	1800	450	-8.2 ± 0.4	5117 ± 58	2.67 ± 0.11	-0.10 ± 0.08	1.43 ± 0.10	G5III
HD 32923	2009 Feb 9	300	200	20.8 ± 0.3	5702 ± 81	4.18 ± 0.11	-0.17 ± 0.06	0.98 ± 0.08	G4V
HD 33636	2008 Dec 19	4800	350	5.6 ± 0.3	6040 ± 93	4.61 ± 0.12	-0.07 ± 0.11	1.03 ± 0.07	G0VH-03
HD 39587	2009 Feb 9	240	300	-12.1 ± 0.7	5996 ± 91	4.53 ± 0.11	$+0.00\pm0.04$	1.00 ± 0.07	G0V
HD 48682	2008 Dec 19	2400	500	-23.9 ± 0.3	6144 ± 96	4.43 ± 0.12	$+0.13\pm0.07$	1.14 ± 0.10	G0V
HD 50692	2008 Apr 25	1200	200	-15.0 ± 0.4	5991 ± 90	4.59 ± 0.12	-0.12 ± 0.05	1.04 ± 0.09	G0V
HD 55575	2008 Apr 25	1080	250	84.8 ± 0.3	5971 ± 91	4.42 ± 0.12	-0.25 ± 0.04	0.97 ± 0.09	G0V
HD 72905	2008 Dec 18	1500	450	-12.7 ± 0.6	5920 ± 88	4.57 ± 0.11	-0.02 ± 0.05	1.08 ± 0.10	G1.5Vb
HD 84737	2008 Dec 19	1309	500	5.0 ± 0.3	5958 ± 89	4.19 ± 0.11	$+0.15\pm0.05$	1.14 ± 0.09	G0.5Va
HD 109358	2008 Apr 24	480	400	6.4 ± 0.3	5912 ± 88	4.48 ± 0.12	-0.21 ± 0.06	1.05 ± 0.08	G0V
HD 110897	2008 Apr 27	1500	150	80.2 ± 0.4	5805 ± 86	4.32 ± 0.12	-0.54 ± 0.08	0.67 ± 0.09	G0V
HD 137510	2008 Apr 27	2400	200	-6.8 ± 0.4	5973 ± 92	4.01 ± 0.11	$+0.29\pm0.12$	1.24 ± 0.08	G0IV-V
HD 141004	2008 Apr 24	480	400	-66.0 ± 0.3	5951 ± 91	4.28 ± 0.12	$+0.00\pm0.06$	1.11 ± 0.11	G0V
HD 161797	2008 Apr 27	120	250	-17.8 ± 0.2	5621 ± 78	4.06 ± 0.10	$+0.31 \pm 0.06$	0.97 ± 0.06	G5IV
HD 188512	2008 Apr 24	240	300	-39.5 ± 0.2	5134 ± 76	3.76 ± 0.11	-0.10 ± 0.07	0.79 ± 0.09	G8IV

Notes.

^a Radial velocities that were obtained from center wavelengths via the measurements of equivalent widths.

^b Spectral type from the SIMBAD database.

using the master flat image, which is combined with all flat images. After aperture tracing, the flat, comparison, and object spectra were extracted from each image, using the same aperture reference of the master flat image. In the flat-fielding process, the interference fringes and pixel-to-pixel variations of spectra were corrected. Wavelength calibration was performed with the ThAr lamp spectrum, and the spectra of objects were normalized in each aperture using the continuum task.

Line List								
Element	λ	E.P.	log gf	EW_{\odot}	$\log \epsilon_{\odot}$			
Nai	5688.19	2.10	-0.42	134.4	6.22			
Naı	6154.23	2.10	-1.53	38.3	6.26			
Naı	6160.75	2.10	-1.32	57.0	6.32			
Mgi	5711.09	4.34	-1.72	116.4	7.58			
Mgi	6319.24	5.11	-2.32	26.7	7.62			
Alı	6696.03	3.14	-1.57	38.1	6.50			
Alı	6698.67	3.14	-1.88	21.6	6.48			
Alı	7836.13	4.02	-0.56	61.7	6.51			

Table 2

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

3. SPECTROSCOPIC ANALYSIS

3.1. Measurement of Equivalent Widths and Radial Velocity

To find the elemental abundances of the stellar atmosphere, we measure the equivalent widths (EWs) of the relevant atomic lines. The measurement of EWs was carried out using the TAME (Tools for Automatic Measurement of Equivalent-widths) program that we developed for the abundance analysis; it has a graphical user interface (GUI). In order to run the TAME the spectra, line list, and parameter file are required. The TAME program runs in three steps.

(1) The TAME determines the local continuum of the spectrum in the wavelength range near the target line of the line list. The range to determine the local continuum can be adjusted. (2) The code finds the lines on the locally normalized spectrum using its derivatives. Using the second and third derivatives, the centers of absorption lines can be easily detected. (3) If there are blended lines near the target line, it fits those lines to the Gaussian/Voigt profile and measures the EW of the target line separately from nearby lines.

For the abundance analysis, the spectral lines of 12 elements (Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Co, Ni) were adopted from Bond et al. (2006), Cohen et al. (2009), and Gilli et al. (2006, hereafter G06). To determine parameters of the model atmosphere, the Fe lines were adopted from Allende Prieto & Garcia Lopez (1998) and the Vienna Atomic Line Database (VALD⁴; Piskunov et al. 1995; Kupka et al. 1999). For accurate estimation of abundances, these Fe lines were examined using the solar spectrum obtained via BOES, and we selected the reliable lines that were not severely blended with nearby lines and were neither too strong nor too weak. The value of oscillator strength (log gf value) for each line was modified to the most recent value from VALD. The line list for EW measurements are listed in Table 2.

The TAME also estimates the center wavelength and full width at half maximum of the target line. We calculated the radial velocities from the center wavelength of the fitting profile. For each star, about 260 lines were used for the measurements, and the standard deviation within those lines was about 0.40 km s^{-1} . The radial velocities are listed in Column 5 of Table 1. We compared these results with those of other studies for radial velocity (Wilson 1953; Nordström et al. 2004; Valenti & Fischer 2005) in Figure 2, which shows good agreement. The radial velocities of HD 17156 and BD+20 518 have been newly determined in this study, and HD 13974 was found to be a spectroscopic binary (Halbwachs et al. 2003).

Figure 2. Radial velocities of this work and a reference (from SIMBAD) for 49 target stars.

3.2. Model Atmosphere

We constructed the model atmosphere for each star using a model grid from Kurucz ATLAS9, without the overshooting mode and with new opacity distribution functions (Kurucz 1993; Castelli & Kurucz 2004). The atmospheric parameters of the Kurucz model atmosphere were determined by a selfconsistent fine analysis, using the FeI and FeII abundances. The fine analysis was carried out by iterations to obtain the abundances of FeI and FeII lines in a model atmosphere and change atmospheric parameters. The effective temperature and microturbulence parameters were adopted by iterating until the dependence of the Fe1 abundance on excitation potential and EW was diminished. The surface gravity was iteratively modified until the mean abundances of Fe I and Fe II were the same. In order to reduce systematic errors from determination of model parameters, this process was automated by IDL code, and thus we were able to obtain model parameters for each star with an identical method. To test the process of this fine analysis, the atmospheric parameters of the Sun were determined using the solar spectrum obtained from BOES from the twilight on 2007 May 10; the values were $T_{\rm eff} = 5765 \pm 86$ K, $\log g = 4.46 \pm 0.11$ dex, [Fe/H] = 0.01 ± 0.05 , and $\xi_t = 0.82 \pm 0.09$ km s⁻¹. Using this atmosphere model, the solar Fe abundances of $\log \epsilon(\text{Fe I}) = 7.53 \pm 0.05$ dex and $\log \epsilon(\text{Fe II}) = 7.53 \pm$ 0.02 dex were obtained, as shown in Figure 3. This value has good agreement with the solar Fe abundance of log ϵ (Fe) = 7.50 dex from Grevesse & Sauval (1998).

In this uniform way, the atmospheric parameters and Fe abundance for 52 stars were determined. We compared these atmospheric parameters, determined by fine analysis, with those of other studies (Cayrel de Strobel et al. 2001; Valenti & Fischer 2005; G06). The differences of atmospheric parameters between this work and all references are about 48 ± 70 K in T_{eff} , 0.03 \pm 0.14 dex in log g, and 0.05 \pm 0.05 dex

¹⁰⁰ $\mathsf{N}_{\mathsf{Stars}}$ = 49 $<\Delta RV> = -0.0084 \pm 1.1926$ $<\sigma_{\rm RV,Lines}> = 0.4015$ $\langle N_{Lines} \rangle = 262$ 50 RV(This Work) [km/s] ſ -50 -100 -2 -100 -50 0 50 100 RV(References) [km/s]

⁴ http://vald.astro.univie.ac.at



Figure 3. Result of the fine analysis using Fe lines of the Sun. This plot shows the abundances for each Fe line (left: Fe I; right: Fe II). The top and bottom panels show the dependence of Fe abundance on excitation potential and EW of the line, respectively. (A color version of this figure is available in the online journal.)



Figure 4. Atmospheric parameters of this study and the three references (Cayrel de Strobel et al. 2001; Valenti & Fischer 2005; Gilli et al. 2006). The numbers in parentheses indicate the number of targets common to this study and the references. The effective temperature, surface gravity, and metallicity parameters are determined to be in good agreement with those of all references. The mean differences in effective temperature, surface gravity, and metallicity are less than 100 K, 0.1 dex, and 0.05 dex, respectively.

(A color version of this figure is available in the online journal.)

in [Fe/H]. As shown in Figure 4, these parameters have good agreement with those of those three references.

3.3. Abundance Analysis and Uncertainties

We determined the elemental abundances via local thermodynamic equilibrium analysis relative to the solar abundances. After measuring the EWs of spectral lines for 13 elements, including iron, the chemical abundances were derived with the 2002 version of the MOOG code⁵ (Sneden 1973) using the abfind driver. The Kurucz ATLAS9 model atmosphere determined by fine analysis of Fe1/II lines was used as the model atmosphere in the MOOG code. First, we derived the solar abundances of 12 elements from the EWs of elemental lines in the solar spectrum, observed with the same spectrometer, BOES. The elemental abundances for 52 stars were obtained using the same method to derive the solar abundance. Comparing the abundances of the Sun and 52 sample stars, we determined the differential abundances. The abundance results for each element are listed in Tables 3 and 4.

⁵ http://www.as.utexas.edu/~chris/moog.html

Table 3									
Chemical Abundances of Na, Mg, Al, Si, Ca, and Sc	;								

			-			
Star	[Na/H]	[Mg/H]	[Al/H]	[Si/H]	[Ca/H]	[Sc/H]
34 Planet-host	Stars					
HD 10697	0.18 ± 0.04	0.13 ± 0.03	0.19 ± 0.06	0.14 ± 0.05	0.12 ± 0.08	0.27 ± 0.04
HD 16141	0.05 ± 0.12	0.14 ± 0.04	0.09 ± 0.03	0.07 ± 0.04	0.11 ± 0.05	0.21 ± 0.05
HD 16400	0.16	0.08 ± 0.01	0.10 ± 0.05	0.11 ± 0.08	0.07 ± 0.04	0.12 ± 0.09
HD 17156	0.27 ± 0.03	0.23 ± 0.16	0.29 ± 0.11	0.23 ± 0.07	0.21 ± 0.12	0.33 ± 0.10
BD+20 518	0.36 ± 0.03	0.26 ± 0.03	0.28 ± 0.06	0.35 ± 0.10	0.31 ± 0.11	0.54 ± 0.00
HD 20367	0.05 ± 0.03	0.02	-0.01 ± 0.03	0.07 ± 0.10	0.17 ± 0.10	0.09 ± 0.03
HD 28305	0.33 ± 0.06	0.14 ± 0.12	0.28 ± 0.06	0.17 ± 0.03	0.06 ± 0.05	0.17 ± 0.12
HD 37124	-0.40 ± 0.05	-0.11 ± 0.13	-0.18 ± 0.06	-0.33 ± 0.06	-0.35 ± 0.04	-0.19 ± 0.01
HD 38529	0.50 ± 0.17	0.39 ± 0.12	0.45 ± 0.12	0.37 ± 0.12	0.32 ± 0.11	0.64 ± 0.21
HD 43691	0.37 ± 0.03	0.17 ± 0.11	0.25 ± 0.03	0.25 ± 0.08	0.27 ± 0.10	0.38 ± 0.06
HD 45350	0.24 ± 0.03	0.29 ± 0.05	0.30 ± 0.04	0.23 ± 0.07	0.24 ± 0.09	0.42 ± 0.09
HD 52265	0.25 ± 0.03	0.18 ± 0.10	0.17 ± 0.06	0.25 ± 0.10	0.23 ± 0.09	0.27 ± 0.04
HD 74156	0.17 ± 0.04	0.11 ± 0.05	0.10 ± 0.01	0.09 ± 0.09	0.11 ± 0.10	0.22 ± 0.05
HD 75732	0.37 ± 0.03	0.35 ± 0.04	0.44 ± 0.08	0.42 ± 0.10	0.30 ± 0.09	0.35 ± 0.02
HD 75898	0.33 ± 0.05	0.15	0.22 ± 0.02	0.25 ± 0.10	0.30 ± 0.11	0.38 ± 0.10
HD 81040	-0.24 ± 0.04	-0.05 ± 0.03	-0.19 ± 0.02	-0.12 ± 0.09	-0.01 ± 0.05	-0.05 ± 0.04
HD 88133	0.26 ± 0.09	0.36 ± 0.10	0.39 ± 0.05	0.34 ± 0.12	0.31 ± 0.12	0.52 ± 0.08
HD 89307	-0.16 ± 0.05	-0.08 ± 0.11	-0.16 ± 0.03	-0.12 ± 0.06	-0.11 ± 0.10	-0.04 ± 0.02
HD 92788	0.27 ± 0.07	0.24 ± 0.12	0.30 ± 0.04	0.27 ± 0.10	0.23 ± 0.10	0.45 ± 0.01
HD 95128	0.01 ± 0.06	0.01 ± 0.07	0.00 ± 0.01	0.02 ± 0.09	-0.06 ± 0.10	0.07 ± 0.06
HD 104985	-0.23 ± 0.03	-0.04 ± 0.03	0.03 ± 0.02	-0.00 ± 0.12	-0.26 ± 0.02	0.04 ± 0.17
HD 106252	-0.04 ± 0.04	-0.16 ± 0.06	0.01 ± 0.08	-0.11 ± 0.09	-0.07 ± 0.08	0.05 ± 0.09
HD 117176	-0.18 ± 0.06	0.01 ± 0.07	0.02 ± 0.04	-0.05 ± 0.09	-0.06 ± 0.11	0.15 ± 0.02
HD 143761	-0.21 ± 0.02	-0.01 ± 0.18	-0.05 ± 0.06	-0.16 ± 0.09	-0.12 ± 0.08	-0.02 ± 0.06
HD 149026	0.42 ± 0.04	0.13	0.28 ± 0.07	0.33 ± 0.09	0.31 ± 0.08	0.55 ± 0.03
HD 154345	-0.24 ± 0.06	-0.11 ± 0.07	-0.13 ± 0.04	-0.15 ± 0.09	-0.12 ± 0.10	-0.02 ± 0.08
HD 155358	-0.58 ± 0.04	-0.47 ± 0.08	-0.55 ± 0.07	-0.53 ± 0.09	-0.47 ± 0.09	-0.36 ± 0.08
HD 185269	0.14 ± 0.01	0.04 ± 0.04	0.10 ± 0.03	0.09 ± 0.07	0.19 ± 0.10	0.25 ± 0.05
HD 186427	0.03 ± 0.03	0.04 ± 0.06	0.06 ± 0.02	0.03 ± 0.05	0.02 ± 0.10	0.20 ± 0.08
HD 190228	-0.32 ± 0.05	-0.16 ± 0.07	-0.23 ± 0.04	-0.29 ± 0.10	-0.22 ± 0.10	-0.16 ± 0.06
HD 190360	0.19 ± 0.06	0.27 ± 0.05	0.31 ± 0.05	0.27 ± 0.08	0.19 ± 0.11	0.38 ± 0.04
HD 195019	-0.01 ± 0.04	0.03 ± 0.07	0.05 ± 0.02	0.01 ± 0.08	0.03 ± 0.11	0.17 ± 0.11
HD 209458	-0.04 ± 0.04	-0.09	-0.03 ± 0.06	-0.01 ± 0.08	0.00 ± 0.07	0.08 ± 0.06
HD 217014	0.21 ± 0.05	0.17 ± 0.07	0.22 ± 0.02	0.15 ± 0.05	0.19 ± 0.07	0.33 ± 0.07
18 Comparison	Stars					
HD 10307	0.04 ± 0.05	-0.00 ± 0.09	0.03 ± 0.02	0.03 ± 0.07	0.02 ± 0.11	0.09 ± 0.08
HD 13974	-0.34 ± 0.16	-0.57	-0.55 ± 0.02	-0.49 ± 0.11	-0.40 ± 0.12	-0.54 ± 0.06
HD 24040	0.18 ± 0.05	0.20 ± 0.08	0.21 ± 0.08	0.16 ± 0.07	0.18 ± 0.10	0.37 ± 0.07
HD 26722	0.11 ± 0.12	-0.11 ± 0.05	-0.10 ± 0.06	-0.00 ± 0.11	-0.10 ± 0.10	0.05 ± 0.18
HD 32923	-0.20 ± 0.05	-0.09 ± 0.04	-0.03 ± 0.02	-0.12 ± 0.10	-0.13 ± 0.09	-0.04 ± 0.04
HD 33636	-0.17 ± 0.04	-0.03 ± 0.13	-0.16 ± 0.02	-0.13 ± 0.07	-0.13 ± 0.08	0.01 ± 0.00
HD 39587	-0.16 ± 0.02	-0.11 ± 0.10	-0.11	-0.10 ± 0.07	0.01 ± 0.07	0.05 ± 0.04
HD 48682	0.09 ± 0.06	0.03 ± 0.03	0.01 ± 0.03	0.08 ± 0.09	0.11 ± 0.08	0.12 ± 0.05
HD 50692	-0.16 ± 0.03	-0.03 ± 0.10	-0.13 ± 0.07	-0.13 ± 0.09	-0.08 ± 0.10	0.01 ± 0.03
HD 55575	-0.36 ± 0.03	-0.04 ± 0.08	-0.29 ± 0.07	-0.30 ± 0.07	-0.22 ± 0.07	-0.20 ± 0.06
HD 72905	-0.17 ± 0.04	-0.12 ± 0.16	-0.11 ± 0.01	-0.13 ± 0.07	-0.04 ± 0.06	-0.06 ± 0.09
HD 84737	0.10 ± 0.06	0.15 ± 0.09	0.12 ± 0.04	0.13 ± 0.10	0.14 ± 0.10	0.28 ± 0.09
HD 109358	-0.18 ± 0.04	-0.13 ± 0.06	-0.21 ± 0.01	-0.22 ± 0.09	-0.21 ± 0.11	-0.14 ± 0.01
HD 110897	-0.61 ± 0.06	-0.42 ± 0.06	-0.53 ± 0.07	-0.48 ± 0.05	-0.47 ± 0.08	-0.53 ± 0.03
HD 137510	0.50 ± 0.10	0.16 ± 0.08	0.32 ± 0.04	0.33 ± 0.08	0.25 ± 0.10	0.42 ± 0.02
HD 141004	-0.01 ± 0.05	0.03 ± 0.05	0.03 ± 0.01	-0.02 ± 0.09	0.02 ± 0.09	0.14 ± 0.05
HD 161797	0.34 ± 0.13	0.26 ± 0.01	0.36 ± 0.02	0.30 ± 0.10	0.27 ± 0.09	0.47 ± 0.10
HD 188512	-0.27 ± 0.11	-0.08 ± 0.07	-0.13 ± 0.04	-0.16 ± 0.10	-0.13 ± 0.11	0.02 ± 0.08

In this case, because the abundances were mainly determined via the measurement of EWs, the systematic error could come from this measurement. By comparing the line profile of the spectrum with either a Gaussian or Voigt profile, we excluded the EWs of lines that were severely blended with some unknown lines. The local continuum level is another culprit for the error of EW measurement, so we also excluded the lines that were located in the crowded region in which it was difficult to determine the local continuum in the spectrum.

Systematic errors can also arise from the uncertainty of stellar parameters that are used to make an atmosphere model. If the parameters for a model atmosphere are not correct, the unexpected errors of abundances can occur. Because this error was combined with EW measurement errors, it is hard to

 Table 4

 Chemical Abundances of Ti, V, Cr, Mn, Co, and Ni

Star	[Ti _I /H]	$[Ti_{II}/H]$	[V/H]	[Cr/H]	[Mn/H]	[Co/H]	[Ni/H]
34 Planet-hos	t Stars						
HD 10697	0.19 ± 0.07	0.20 ± 0.10	0.16 ± 0.05	0.08 ± 0.05	0.71	0.19 ± 0.06	0.18 ± 0.07
HD 16141	0.17 ± 0.06	0.22 ± 0.07	0.13 ± 0.06	0.07 ± 0.05	0.04 ± 0.03	0.14 ± 0.07	0.12 ± 0.05
HD 16400	0.17 ± 0.07	0.14 ± 0.03	0.27 ± 0.09	0.13 ± 0.03	0.05	0.29 ± 0.11	0.08 ± 0.07
HD 17156	0.29 ± 0.10	0.31 ± 0.04	0.29 ± 0.04	0.22 ± 0.08	0.49	0.20 ± 0.09	0.25 ± 0.07
BD+20 518	0.35 ± 0.11	0.18 ± 0.08	0.43 ± 0.09	0.30 ± 0.11	0.32	0.47 ± 0.08	0.40 ± 0.06
HD 20367	0.18 ± 0.09	0.15 ± 0.13	0.18 ± 0.05	0.14 ± 0.08	0.18 ± 0.12	0.06 ± 0.09	0.07 ± 0.06
HD 28305	0.20 ± 0.08	0.10 ± 0.17	0.39 ± 0.17	0.18 ± 0.11	0.22	0.41 ± 0.09	0.14 ± 0.05
HD 37124	-0.12 ± 0.05	-0.19 ± 0.08	-0.17 ± 0.07	-0.49 ± 0.01	-0.44 ± 0.06	-0.28 ± 0.03	-0.42 ± 0.05
HD 38529	0.44 ± 0.12	0.40 ± 0.18	0.48 ± 0.06	0.30 ± 0.03	0.36 ± 0.05	0.50 ± 0.08	0.45 ± 0.06
HD 43691	0.28 ± 0.05	0.35 ± 0.07	0.33 ± 0.05	0.26 ± 0.09	0.18 ± 0.06	0.29 ± 0.10	0.32 ± 0.05
HD 45350	0.36 ± 0.06	0.34 ± 0.12	0.37 ± 0.03	0.23 ± 0.01	0.26 ± 0.05	0.36 ± 0.09	0.32 ± 0.04
HD 52265	0.30 ± 0.09	0.27 ± 0.15	0.28 ± 0.05	0.20 ± 0.09	0.38	0.16 ± 0.02	0.24 ± 0.06
HD 74156	0.22 ± 0.06	0.20 ± 0.11	0.17 ± 0.04	0.11 ± 0.10	0.35	0.09 ± 0.10	0.15 ± 0.05
HD 75732	0.38 ± 0.05	0.16 ± 0.12	0.65 ± 0.18	0.37 ± 0.06	0.37	0.53 ± 0.11	0.43 ± 0.08
HD 75898	0.32 ± 0.10	0.43 ± 0.08	0.37 ± 0.05	0.25 ± 0.09	0.56	0.33 ± 0.06	0.32 ± 0.05
HD 81040	-0.02 ± 0.08	-0.04 ± 0.09	-0.06 ± 0.09	-0.12 ± 0.06	0.13	-0.17 ± 0.09	-0.16 ± 0.08
HD 88133	0.36 ± 0.12	0.43 ± 0.14	0.43 ± 0.07	0.30 ± 0.05	0.34 ± 0.05	0.54 ± 0.10	0.41 ± 0.07
HD 89307	0.01 ± 0.08	0.01 ± 0.05	-0.15 ± 0.05	-0.13 ± 0.05	-0.07 ± 0.07	-0.18 ± 0.09	-0.17 ± 0.04
HD 92788	0.31 ± 0.10	0.29 ± 0.12	0.34 ± 0.03	0.20 ± 0.03	0.26	0.38 ± 0.12	0.34 ± 0.08
HD 95128	0.07 ± 0.09	0.04 ± 0.09	0.02 ± 0.06	-0.03 ± 0.07	0.06 ± 0.13	-0.01 ± 0.08	-0.02 ± 0.07
HD 104985	-0.03 ± 0.06	-0.06 ± 0.13	0.12 ± 0.17	-0.34 ± 0.12	-0.43	0.06 ± 0.12	-0.25 ± 0.06
HD 106252	0.05 ± 0.08	0.09 ± 0.02	0.04 ± 0.08	-0.06 ± 0.10	0.15	-0.02 ± 0.09	-0.05 ± 0.04
HD 117176	0.04 ± 0.08	0.13 ± 0.09	0.04 ± 0.08	-0.07 ± 0.09	-0.11	0.01 ± 0.09	-0.08 ± 0.05
HD 143761	0.05 ± 0.07	0.02 ± 0.09	-0.05 ± 0.06	-0.20 ± 0.07	-0.14	-0.10 ± 0.12	-0.20 ± 0.03
HD 149026	0.47 ± 0.08	0.56 ± 0.06	0.43 ± 0.04	0.36 ± 0.12	0.69	0.41 ± 0.06	0.44 ± 0.06
HD 154345	0.04 ± 0.11	-0.05 ± 0.10	0.01 ± 0.08	-0.07 ± 0.08	-0.06	-0.02 ± 0.05	-0.10 ± 0.05
HD 155358	-0.36 ± 0.09	-0.28 ± 0.12	-0.47 ± 0.16	-0.58 ± 0.14	-0.81 ± 0.11	-0.62 ± 0.06	-0.69 ± 0.03
HD 185269	0.19 ± 0.08	0.34 ± 0.12	0.17 ± 0.10	0.10 ± 0.10	0.26	0.13 ± 0.02	0.13 ± 0.02
HD 186427	0.14 ± 0.05	0.15 ± 0.10	0.12 ± 0.08	0.05 ± 0.09	0.53	0.15 ± 0.08	0.08 ± 0.04
HD 190228	-0.19 ± 0.05	-0.09 ± 0.17	-0.21 ± 0.02	-0.37 ± 0.04	-0.29	-0.23 ± 0.06	-0.33 ± 0.03
HD 190360	0.32 ± 0.11	0.30 ± 0.11	0.35 ± 0.05	0.17 ± 0.04		0.40 ± 0.11	0.28 ± 0.01
HD 195019	0.10 ± 0.07	0.06 ± 0.08	0.06 ± 0.04	-0.01 ± 0.06	0.26	0.01 ± 0.06	0.01 ± 0.04
HD 209458	0.12 ± 0.10	0.07 ± 0.09	0.03 ± 0.05	0.02 ± 0.05	0.07	-0.02 ± 0.10	-0.02 ± 0.04
HD 217014	0.30 ± 0.08	0.24 ± 0.09	0.29 ± 0.05	0.15 ± 0.01	0.22 ± 0.05	0.30 ± 0.07	0.28 ± 0.07
18 Compariso	on Stars						
HD 10307	0.08 ± 0.10	0.12 ± 0.05	0.11 ± 0.05	0.02 ± 0.08	-0.01 ± 0.03	0.05 ± 0.04	0.04 ± 0.04
HD 13974	-0.38 ± 0.08	-0.30 ± 0.13	-0.48 ± 0.05	-0.54 ± 0.06	-0.51	-0.56 ± 0.08	-0.53 ± 0.03
HD 24040	0.29 ± 0.06	0.39 ± 0.07	0.34 ± 0.08	0.21 ± 0.08	0.07 ± 0.06	0.34 ± 0.04	0.26 ± 0.06
HD 26722	-0.04 ± 0.12	-0.01 ± 0.18	-0.12 ± 0.05	-0.19 ± 0.06	-0.39 ± 0.12	-0.04 ± 0.15	-0.15 ± 0.06
HD 32923	0.01 ± 0.08	0.02 ± 0.05	-0.12 ± 0.08	-0.23 ± 0.06	-0.25	-0.14 ± 0.09	-0.21 ± 0.04
HD 33636	0.02 ± 0.09	-0.01 ± 0.08	-0.07 ± 0.06	-0.14 ± 0.06	-0.25	-0.09 ± 0.10	-0.15 ± 0.04
HD 39587	0.10 ± 0.09	0.15 ± 0.08	0.03 ± 0.05	0.04 ± 0.08	-0.12	-0.03	-0.08 ± 0.05
HD 48682	0.16 ± 0.10	0.20 ± 0.08	0.09 ± 0.03	0.01 ± 0.02	0.03	0.07 ± 0.02	0.09 ± 0.05
HD 50692	-0.02 ± 0.10	-0.07 ± 0.09	-0.13 ± 0.10	-0.16 ± 0.07	-0.23	-0.11 ± 0.10	-0.17 ± 0.05
HD 55575	-0.14 ± 0.08	-0.10 ± 0.08	-0.28 ± 0.06	-0.39 ± 0.06	-0.55	-0.32 ± 0.05	-0.38 ± 0.06
HD 72905	0.04 ± 0.07	0.02 ± 0.06	-0.02 ± 0.08	-0.04 ± 0.09	-0.18	-0.10 ± 0.00	-0.14 ± 0.04
HD 84737	0.14 ± 0.10	0.33 ± 0.08	0.14 ± 0.10	0.05 ± 0.04	0.06 ± 0.01	0.14 ± 0.03	0.13 ± 0.05
HD 109358	-0.04 ± 0.11	-0.08 ± 0.05	-0.12 ± 0.09	-0.20 ± 0.08	-0.20	-0.22 ± 0.01	-0.22 ± 0.04
HD 110897	-0.49 ± 0.10	-0.46 ± 0.11	-0.52 ± 0.10	-0.51 ± 0.05	-0.92	-0.62 ± 0.04	-0.62 ± 0.09
HD 137510	0.28 ± 0.09	0.46 ± 0.12	0.30 ± 0.10	0.23 ± 0.10	0.34	0.29 ± 0.04	0.35 ± 0.05
HD 141004	0.10 ± 0.11	0.19 ± 0.12	0.05 ± 0.06	-0.06 ± 0.05	0.00	-0.00 ± 0.05	0.01 ± 0.03
HD 161797	0.37 ± 0.07	0.58 ± 0.14	0.44 ± 0.08	0.27 ± 0.05	0.26 ± 0.08	0.45 ± 0.05	0.35 ± 0.05
HD 188512	-0.04 ± 0.05	0.05 ± 0.12	0.00 ± 0.09	-0.15 ± 0.09	-0.20	0.01 ± 0.07	-0.18 ± 0.04

define separately but can be predicted by the variation of model parameters. Hence, we examined the sensitivity of abundances to the model parameters. The stellar parameters of the model atmosphere were changed by 100 K for T_{eff} , 0.3 dex for [Fe/H], 0.3 dex for log g, and 0.3 km s⁻¹ for microturbulence (ξ_1). The abundance sensitivities to changes in the parameters of the model atmosphere are displayed in Table 5. The sample stars were selected so that a testing parameter could be gradually

changed while other parameters varied as little as possible. Table 5 shows that most elements are insensitive to varying stellar parameters within 0.13 dex. The abundances of Sc II and Ti II are the most sensitive to surface gravity because these elements are almost singly ionized around the temperature of the solar atmosphere; these ionized lines are sensitive to gravity due to the H⁻ continuum opacity, which is related to electron pressure. The largest variation in Sc II and Ti II abundances is,

 Table 5

 The Sensitivity of Abundances to the Model Parameters for Each Element

Name	Naı	Мg I	Alı	Siı	Сат	Scп	Тi г	Тіп	VI	Crı	Мп I	Сот	Ni 1
$(T_{\rm eff}, [{\rm Fe}/{\rm H}], \log g, \xi_{\rm t})$													
					T _{eff} ;	±100 K							
HD 209458	-0.05	-0.05	-0.03	-0.03	-0.06	-0.01	-0.08	-0.01	-0.09	-0.05	-0.09	-0.07	-0.06
(6127, 0.02, 4.43, 1.16)	+0.04	+0.04	+0.03	+0.03	+0.06	+0.01	+0.08	+0.00	+0.09	+0.05	+0.09	+0.07	+0.06
HD 106252	-0.05	-0.04	-0.04	-0.02	-0.06	-0.00	-0.09	+0.00	-0.10	-0.06	-0.12	-0.06	-0.06
(5976, -0.02, 4.56, 0.93)	+0.05	+0.04	+0.04	+0.03	+0.06	+0.01	+0.09	+0.00	+0.09	+0.05	+0.11	+0.07	+0.06
HD 154345	-0.06	-0.03	-0.04	+0.00	-0.08	+0.00	-0.11	+0.01	-0.12	-0.07	-0.10	-0.06	-0.03
(5452, -0.08, 4.54, 0.46)	+0.06	+0.04	+0.05	+0.00	+0.07	-0.01	+0.11	-0.01	+0.12	+0.07	+0.10	+0.06	+0.04
					[Fe/H];	$\pm 0.30 \text{ dex}$							
HD 155358	-0.02	-0.02	-0.01	-0.02	-0.03	-0.05	-0.03	-0.04	-0.04	-0.02	-0.04	-0.03	-0.03
(5944, -0.63, 4.27, 1.06)	-0.01	-0.01	-0.01	-0.00	-0.00	+0.06	-0.03	+0.06	-0.03	-0.02	-0.03	-0.02	-0.01
HD 50692	-0.04	-0.03	-0.02	-0.04	-0.04	-0.07	-0.03	-0.06	-0.03	-0.03	-0.05	-0.04	-0.03
(5911, -0.17, 4.44, 0.98)	+0.01	+0.01	-0.00	+0.03	+0.02	+0.08	-0.01	+0.08	-0.01	+0.00	+0.00	+0.00	+0.01
HD 24040	-0.03	-0.02	-0.00	-0.04	-0.04	-0.10	+0.00	-0.09	+0.01	-0.00	-0.01	-0.01	-0.02
(5915, 0.24, 4.41, 0.98)	+0.04	+0.03	+0.01	+0.05	+0.04	+0.10	+0.01	+0.09	+0.01	+0.02	+0.03	+0.03	+0.03
					log <i>g</i> ; =	±0.30 dex							
HD 26722	+0.04	+0.01	+0.01	-0.02	+0.04	-0.13	+0.01	-0.13	+0.01	+0.01	+0.01	-0.02	-0.02
(5117, -0.10, 2.67, 1.43)	-0.04	-0.02	-0.02	+0.02	-0.05	+0.12	-0.01	+0.12	-0.01	-0.01	-0.01	+0.02	+0.02
HD 188512	+0.06	+0.03	+0.02	-0.02	+0.09	-0.12	+0.02	-0.11	+0.01	+0.02	+0.02	-0.03	-0.02
(5134, -0.10, 3.76, 0.79)	-0.06	-0.04	-0.03	+0.02	-0.09	+0.11	-0.02	+0.10	-0.01	-0.02	-0.02	+0.04	+0.02
HD 154345	+0.06	+0.04	+0.03	-0.00	+0.11	-0.12	+0.02	-0.11	+0.01	+0.02	+0.01	-0.03	-0.00
(5452, -0.08, 4.54, 0.46)	-0.06	-0.04	-0.03	+0.01	-0.11	+0.11	-0.03	+0.10	-0.01	-0.03	-0.02	+0.03	+0.01
					$\xi_t; \pm 0$	0.30 dex							
HD 137510	+0.03	+0.03	+0.02	+0.03	+0.07	+0.09	+0.05	+0.11	+0.02	+0.03	+0.01	+0.02	+0.06
(5973, 0.29, 4.01, 1.24)	-0.03	-0.05	-0.02	-0.04	-0.08	-0.09	-0.05	-0.13	-0.02	-0.03	-0.01	-0.02	-0.06
HD 161797A	+0.02	+0.03	+0.02	+0.03	+0.06	+0.09	+0.05	+0.09	+0.06	+0.05	+0.11	+0.04	+0.07
(5621, 0.31, 4.06, 0.97)	-0.03	-0.03	-0.03	-0.04	-0.08	-0.10	-0.05	-0.11	-0.06	-0.05	-0.13	-0.04	-0.08
BD+20 518	+0.02	+0.02	+0.01	+0.02	+0.04	+0.07	+0.05	+0.06	+0.06	+0.04	+0.07	+0.03	+0.06
(5540, 0.30, 4.31, 0.73)	-0.02	-0.02	-0.02	-0.02	-0.05	-0.06	-0.06	-0.07	-0.06	-0.04	-0.10	-0.03	-0.06

however, only about 0.13 dex, with a variation of 0.3 dex of log g. We estimated the uncertainties of effective temperature and microturbulence by probing the slope of Fe abundances of excitation potentials and EWs, and the uncertainty of surface gravity was adopted from exploring the abundance difference between FeI and FeII. The uncertainties are listed in Table 1, with stellar parameters. Considering that the uncertainty of log g, which is the most sensitive to abundances, is within 0.15 dex (Figure 4), the abundance error that comes from the uncertainties of stellar parameters is acceptable.

4. RESULTS

4.1. The Metallicities of PHSs

According to studies of the correlation between the presence of a planet and metallicity (Fischer & Valenti 2005; Johnson et al. 2010), metallicity is very crucial to the formation of planets, especially massive giants. Although the samples in this study are not fully volume limited, we were able to confirm that the PHSs tend to be more metal-rich than comparison stars (Figure 5(a); Santos et al. 2001, 2003, 2004, 2005; Fischer & Valenti 2005; Sousa et al. 2008; Johnson et al. 2010). The relation between metallicity and planetary properties, such as mass and semimajor axis of planetary orbit, was also examined (Figure 5(b)). As shown in Figure 5(b), more massive planets were detected around the PHSs with high [Fe/H] ratios relative to the samples with low [Fe/H] ratios. This relation between planet mass and metallicity has been suggested in previous studies (Ida & Lin 2004; Fischer & Valenti 2005). Because it is very unlikely that one could detect more massive planets in these PHSs by another method of exoplanet detection, it is not expected that this distribution of massive planets will change in the future.

4.2. The Averages and Standard Deviations of Abundances

We carried out abundance analyses of 12 elements for 52 G-type stars. The differences in [X/Fe] between PHSs and comparison stars was examined to estimate the average abundances of each element (Figure 6). The results for these two groups are separately represented for each [Fe/H] bin, whose size is 0.2 dex, and the symbols and error bars indicate the average and standard deviation of each group for each [Fe/H] bin. Because there are different trends of abundances in metal-rich and metal-poor stars in the Galactic chemical evolution, especially for α -elements, it is necessary to investigate the elemental abundances with metallicity. As shown in Figure 6, most α -elements, such as Mg, Ca, and Ti, of PHSs are more abundant and scattered when [Fe/H] < -0.4 relative to comparison stars; [Mn/Fe] shows the most noticeable difference between the PHSs and comparison stars. The differences of most elements, such as Mg, Al, Sc, Ti, V, and Co, are large—as much as about 0.2 dex at [Fe/H] < -0.5—and disappear beyond [Fe/H] -0.3.

The trend of the [X/Fe] ratio for 12 elements with metallicity is shown in Figure 7 for PHSs (red circles) and comparison stars (blue diamonds) separately, with background gray symbols indicating 743 stars from Soubiran & Girard (2005). The right plots of each panel include the abundance of host stars



Figure 5. Histogram of metallicity and the relation between metallicity and planetary properties. In the left plot, red and blue histograms represent the metallicity distributions of PHSs and comparison stars. In the right plot, the *y*-axis is metallicity and the *x*-axis is the semimajor axis of planetary orbit. The symbol size stands for planetary mass, and the red circles connected with dashed lines indicate multi-planet systems. The blue asterisks in the right plot indicate the metallicity of comparison stars.



Figure 6. Averages and standard deviations of abundances for each [Fe/H] bin for dwarf stars. The symbols and error bars indicate the average and standard deviation, respectively, of each bin. The bins are centered at [Fe/H] = -0.5, -0.3, -0.1, 0.1, and 0.3 dex, and the size of the bin is 0.2 dex.

(*y*-axis), the semimajor axis of planetary orbit (*x*-axis), and planetary mass (the size of the symbol).

4.3. Na, Mg, and Al Abundances

The abundances of Na, Mg, and Al show similar trends, which decrease with increasing [Fe/H] until the solar metallicity is reached, and then slightly increase to the region of [Fe/H] > 0 (Figure 7). The trend of these results has good agreement with the abundance results (gray "x" symbols) of Soubiran & Girard (2005) for 743 galactic stars. The [Na/Fe] ratio drastically increases in the stars with [Fe/H] > 0, and the

[Mg/Fe] ratios decrease more steeply than abundances of the other elements when [Fe/H] < 0.

But there are few differences between PHSs and comparison stars, and no relation between the chemical abundances of [Na/Fe], [Mg/Fe], and [Al/Fe] and planetary properties. These trends of [Na/Fe], [Mg/Fe], and [Al/Fe] PHSs and comparison stars also have been shown in the previous results of Gilli et al. (2006) and Neves et al. (2009). The [Mg/Fe] and [Al/Fe] ratios of PHSs are slightly larger than those of comparison stars. The results of both Gilli et al. (2006) and Neves et al. (2009) show a similar trend of [Mg/Fe] to our results. Their [Mg/Fe] ratios of PHSs also seem to be located at the upper boundary of all [Mg/Fe] ratios in low-metallicity samples with [Fe/H] < -0.4.

In the plots with planetary properties in Figure 7, all Na, Mg, and Al results do not show a noticeable relation between abundances and planetary properties. But it is interesting that the HD 37124 dwarf, which has three planets (at 0.53, 1.64, and 3.19 AU) of about 0.6 $M_J \sin i$, shows very high [Mg/Fe] and [Al/Fe] ratios. Because the Al and Mg elements are very important to the condensation process (Lodders 2003) and just as abundant in the solar system as Fe, the fact that HD 37124 has three planets could be related to the high abundances of these Al and Mg elements.

4.4. Si, Ca, Sc, and Ti Abundances

The abundances of Si, Ca, Sc, and Ti show typical trends of α -elements, although [Sc/Fe] shows a larger scatter. The abundances of these elements increase with decreasing metallicity. The large scatter of [Sc/Fe] among the samples may be caused by hyperfine splitting of the Sc II line.

The abundances of Ti and Sc in the stars with [Fe/H] < -0.4 show a large difference between PHSs and comparison stars. Although there are only four stars at [Fe/H] < -0.4, the difference in abundance is larger than the typical error of abundance. This difference in low-metallicity samples also has been found in Si and Ca. In Figure 6, it is obvious that the difference in abundance among Si, Ca, Sc, and Ti becomes larger in the sample of [Fe/H] < -0.4. Although Robinson et al. (2006) suggested that [Ti/Fe] was insensitive to the presence of planets, the [X/Fe] ratios of Si, Ca, Sc, and Ti in Neves et al. (2009) have good agreement with our results when [Fe/H] < -0.4. The results of Neves et al. (2009) also show high



Figure 7. Elemental abundance results: [X/Fe] vs. [Fe/H] (left) and [X/Fe] vs. planetary properties (right). The left plots of each panel show the trends of 12 element abundances [X/Fe] and [Fe/H]. The crosshair at the bottom left of each panel represents typical errors of abundances as the average of errors; the red circles and blue diamonds represent PHSs and comparison stars, respectively; and the symbols with black dots represent giant stars. The gray "x" symbols indicate the results of Soubiran & Girard (2005) for 743 stars. The right side of each panel demonstrates the relation between elemental abundances and planetary properties. The symbols as planets are the same for those used in the plots of Figure 1.

[X/Fe] ratios of Si, Ca, Sc, and Ti for PHSs in low-metallicity samples.

The low-metallicity star HD 155358 ([Fe/H] = -0.63), which has two planets at around 0.63 and 1.22 AU, has high [Ca/Fe], [Ti/Fe], and [Sc/Fe] ratios. HD 37124 ([Fe/H] = -0.43), which has high [Mg/Fe] and [Al/Fe] ratios, also has a high [Ti/Fe] ratio. This could be caused by intrinsic differences in abundances between stars with thick and thin Galactic disks. We discuss the probability that these stars belong to the Galactic thick disk in Section 6.

4.5. V, Cr, and Mn Abundances

The trend of V, Cr, and Mn abundances in Figure 7 seems different from those of α -elements. The abundances of V show a large scatter compared with Cr abundances among all target stars. Cr and V are iron-peak elements that have the same

origin as Fe in the nucleosynthesis process. Despite a large scatter for each star, the V abundances also show a slight difference between PHSs and comparison stars when [Fe/H] < 0, similar to the α -elements shown in [Ti/Fe] and [Sc/Fe] versus [Fe/H] plots of Figure 7, but do not show any difference in the Cr abundances. The low-metallicity star HD 37124 shows a high [V/Fe] ratio that is similar to the high [Mg/Fe] and [Al/Fe] ratios.

For the Mn abundances, the trend of [Mn/Fe] with respect to [Fe/H] is different from those of α -elements and iron-peak elements. The difference between PHSs and comparison stars is over 0.15 dex over the entire range of [Fe/H]. On the other hand, the Mn abundances estimated by G06 also are very scattered, just like our results, but the results of G06 do not show a noticeable difference in [Mn/Fe] between PHSs and comparison stars. It is very difficult to measure the accurate EWs of Mn I lines due to the contamination of nearby lines and hyperfine splitting, so the

 Table 6

 The Averages and Standard Deviations of Abundances

Elements	For 16	6 Dwarfs with [Fe/H] <	: 0	For 32 Dwarfs with $[Fe/H] > 0$			
	[X/Fe] _{PHS}	[X/Fe] _{Comp}	$\Delta [X/Fe]^a$	[X/Fe] _{PHS}	[X/Fe] _{Comp}	$\Delta [X/Fe]^a$	
Naı	-0.04 ± 0.09	-0.04 ± 0.08	0.00	0.01 ± 0.08	-0.01 ± 0.11	0.02	
Mgı	0.08 ± 0.14	0.06 ± 0.12	0.02	-0.04 ± 0.06	-0.07 ± 0.05	0.03	
Alı	0.05 ± 0.12	-0.00 ± 0.07	0.05	-0.00 ± 0.07	-0.03 ± 0.06	0.03	
Siı	0.01 ± 0.07	-0.01 ± 0.05	0.03	-0.01 ± 0.05	-0.03 ± 0.05	0.02	
Сал	0.05 ± 0.07	0.03 ± 0.05	0.02	-0.02 ± 0.04	-0.02 ± 0.02	0.01	
Scп	0.15 ± 0.10	0.08 ± 0.08	0.07	0.12 ± 0.08	0.09 ± 0.06	0.03	
Ti 1	0.16 ± 0.10	0.11 ± 0.05	0.05	0.06 ± 0.04	0.04 ± 0.04	0.02	
VI	0.10 ± 0.09	0.04 ± 0.05	0.07	0.07 ± 0.07	0.04 ± 0.06	0.03	
Crı	-0.00 ± 0.04	-0.03 ± 0.04	0.03	-0.03 ± 0.04	-0.05 ± 0.05	0.01	
Мп I	0.04 ± 0.10	-0.12 ± 0.12	0.16	0.13 ± 0.19	-0.07 ± 0.07	0.20	
Сот	0.04 ± 0.08	-0.01 ± 0.07	0.04	0.05 ± 0.09	0.02 ± 0.07	0.03	
Ni 1	-0.02 ± 0.04	-0.05 ± 0.04	0.03	0.03 ± 0.05	-0.00 ± 0.05	0.03	

Note.^a $\langle [Fe/H] \rangle_{PHSs} - \langle [Fe/H] \rangle_{Comparisons}$.

Mn abundances were determined from only a few lines, which obviously were isolated and well fitted by the Gaussian profile. Even taking into account the scatter from measurements of a few lines, the difference in [Mn/Fe] between PHSs and comparison stars seems not to be due only to errors in determination of abundance. Furthermore, previous studies have presented this discrepancy of [Mn/Fe] between PHSs and comparison stars (Bodaghee et al. 2003; Zhao et al. 2002). This may imply that Mn is somehow related to planet formation.

4.6. Co and Ni Abundances

The abundance trends of Co and Ni are similar to the Fe abundances [Fe/H]. However, the [Co/Fe] ratios show a large scatter compared with [Ni/Fe] ratios. In the [Co/Fe] versus [Fe/H] plot, the [Co/Fe] ratios of PHSs are also slightly higher than those of comparison samples when [Fe/H] < 0.

Although the differences in [Co/Fe] and [Ni/Fe] when [Fe/H] < 0 are small relative to those of the other elements, our trends of [Co/Fe] and [Ni/Fe] in low-metallicity stars show good agreement with those of Neves et al. (2009). The abundances of Co and Ni in stars with planets in Neves et al. (2009) also show slightly higher [X/Fe] ratios than the average [X/Fe] ratios in stars without planets at around [Fe/H] = -0.4.

4.7. Comparison of the Abundances with the Reference

To test how reliable these results are, we compared these abundances with the results adopted from G06. We use the same 19 samples as G06, and Figure 8 shows that our results of elemental abundances, especially [Fe/H] and [Si/H], have good agreement with the results of G06. Except for Mn, our abundances are consistent with the abundances of G06, to within 0.08 dex of standard deviation. The Mn abundances in this work show a large scatter compared with those of G06 and the other elements. Because Mn I lines have a hyperfine structure, these scatters should be examined in detail using hyperfine structure analysis.

5. DISCUSSION

5.1. Abundance Differences Between PHSs and Comparison Stars

We have examined two groups of samples, PHSs and comparison stars (non-PHSs). The average abundances were compared



Figure 8. Abundance differences between this work and G06. The averages and standard deviations of the same sample are indicated on the right side of the plot.

between those two groups only for dwarf samples, in order to eliminate the effects due to convection near the surface. In Table 6, the averages and standard deviations of abundances are shown for dwarf stars in two metallicity ranges: stars with [Fe/ H] < 0 and those with [Fe/H] > 0. For most elements, the abundances of PHSs were slightly larger than those of comparison stars, although the differences are tiny relative to the standard deviations of samples. For most elements, the abundance differences between PHSs and comparison stars of [Fe/H] < 0 were greater than those of [Fe/H] > 0. Thus, we confirmed that differences in elemental abundances are larger in stars with



Figure 9. Cumulative distribution function of [Fe/H] and other elements. The x-axis is [Fe/H] and [X/Fe] of elemental abundances, and the y-axis is the cumulative function of samples. The value of *PROB* shows the significance level of the K-S statistics, and small *PROB* value indicates that the two data sets have different distributions.



Figure 10. Toomre diagram for *U*, *V*, and *W* velocities of our samples. The *U*, *V*, and *W* velocities were calculated from our radial velocities and the proper motions, which were adopted from SIMBAD. This plot shows the Galactic velocities of PHSs (HD 37124 and HD 155358) and comparison stars (HD 13974 and HD 110897) of [Fe/H] < -0.4. Their *V* components are larger than -50 km s^{-1} . For low-metallicity PHSs, the peculiar space velocities $v_{\text{pec}} = (U_{\text{LSR}}^2 + V_{\text{LSR}}^2 + W_{\text{LSR}}^2)^{1/2}$ are also smaller than 70 km s⁻¹.

[Fe/H] < 0. This finding becomes more significant when searching for Earth-class exoplanets, because previous studies of elemental abundances PHSs have suggested that it is more feasible to find these low-mass planets in low-metallicity stars (Udry et al. 2006; Sousa et al. 2008). In Figure 7, we showed that the sample HD 37124, which has low metallicity and high [Mg/Fe], [Al/Fe], [Ti/Fe], and [V/Fe], has three planets of relatively low mass (< 1*M*_J), and that HD 155358, which has high [Ca/Fe], [Sc/Fe], and [Ti/Fe], has two relatively low-mass planets.

5.2. Kolmogorov-Smirnov Test

To evaluate the probability that the abundances of our two groups have the same distribution, the Kolmogorov-Smirnov test (K-S test) was performed. Because the K-S test can investigate the difference in [X/Fe] distributions for a small sample, it is useful to compare the abundance distribution of PHSs with that of comparison stars. The cumulative distribution functions for [Fe/H] and other elements are shown in Figure 9. In Figure 9, the *x*-axis is [Fe/H], or [X/Fe] for elemental abundances, and the *y*-axis is the cumulative function of samples. The value of *PROB* represents the significance level of the K-S statistics, that is, the probability that two distributions belong to the same population. A small *PROB* value means that the two groups of data have different distributions.

For the metallicity distribution, the probability that the [Fe/H] distributions of both groups belong to the same population was about 9%. As shown in the cumulative distribution function of [Mn/Fe] in Figure 9, the probability for the [Mn/Fe] distribution was about 0.0015%, and it was only thousandths of a percent for other elements. Although the sample size was small and there were random errors of abundances, this result shows that the distributions of [Mn/Fe] in each group were severely different. For Cr and Ni, the [X/Fe] of PHSs and comparison stars shows a similar trend over the entire range of [Fe/H] in the left plots of Figure 7. However, the probabilities that the [X/Fe] distributions of Cr and Ni in both groups belong to the same population were only about 7% and 3%, respectively, and smaller than that for metallicity. For the other elements, the probabilities of [X/Fe] distribution.

6. CONCLUDING REMARKS

We have carried out abundance analyses for 12 elements for 34 PHSs and 18 comparison G-type stars. Because it was expected that the differences abundances among samples were as small as about 0.1 dex, we concentrated on minimizing systematic errors. We limited the samples to G-type stars that were similar to the Sun, and the entire process of abundance analysis was restrictively performed in a uniform way. Using the abundances and planetary properties of PHSs, such as planetary mass and the semimajor axis, we plotted the ratios [X/Fe] versus [Fe/H] and [X/Fe] versus the semimajor axis of planetary orbit with planetary mass. In the plot of [Fe/H] and planetary properties, we confirmed that host stars with low metallicity tended to have fewer massive planets.

In previous studies, the authors have made every effort to investigate the statistical differences in abundances only between PHSs and normal-field stars over the entire range of metallicity. The chemical anomalies of PHSs, however, would be noticeable in the stars with low metallicity, because the total amount of metal was insufficient to easily form a planet. In Figure 6, the [X/Fe] ratios of most elements show slight discrepancies between our two groups in the stars of [Fe/H] < -0.4. The [X/Fe] ratios of Mg, Al, Sc, Ti, V, and Co for PHSs are higher than those of comparison stars at [Fe/H] <-0.4 by more than 0.2 dex. HD 37124 (three planets at 0.53, 1.64, and 3.19 AU) and HD 155358 (two planets at 0.63 and 1.22 AU), even though they are metal poor, have several planets with mass less than 1 M_1 . Although there are two samples of PHSs at [Fe/H] < -0.4, as shown in Figure 7, these PHSs imply that the PHSs with low metallicities and high [Mg/Fe], [Al/Fe], [Ca/Fe], [Sc/Fe], [Ti/Fe], and [V/Fe] tend to have low-mass planets, while the metal-rich PHSs tend to have massive planets. When these stars were verified by U, V, and W velocities and their locations in our Galaxy, both stars were to be found located near the Sun and the Galactic plane, and their velocities are small relative to those of the thick-disk stars in Figure 10 (Bensby et al. 2003). So, it is unlikely that these PHSs belong to the Galactic thick disk.

In this study, we found that Mn is the most interesting element. As mentioned above, the [Mn/Fe] ratios of most PHSs are higher than those of comparison stars by as much as about 0.15 dex, and the result of the K-S test implies that the distributions of [Mn/Fe] ratios in our two groups have different populations. Although the Mn abundances were obtained from only a few lines, this large discrepancy in [Mn/Fe] ratios is unlikely to come from the errors in the abundance analysis. Previous studies (Bodaghee et al. 2003; Zhao et al. 2002) also have suggested the difference in [Mn/Fe] between PHSs and comparison stars, though the difference is statistically within their scatter.

Furthermore, the condensation temperature of Mn is lower than other elements. Consequently, in the processes of planet formation, Mn would be condensed later than other elements, where the dust ball had already been formed and planetesimals began to form. Therefore, after the compounds of Ca, Ti, Mg, Al, and Si were first formed, Mn was condensed into their compounds, so even though the amount was tiny, we estimate that Mn played a critical role in the condensation process during this stage, similar to an enzyme in chemical reactions.

In the future, we plan to perform abundance analyses for other, elements non-refractory and extend the samples to F- and K-type stars. Thus, we will follow up a clue about the presence of exoplanets using other elements and more sample stars.

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