

METALLICITIES OF PLANET-HOSTING STARS: A SAMPLE OF GIANTS AND SUBGIANTS*

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Received 2010 June 7; accepted 2010 October 3; published 2010 November 19

ABSTRACT

This work presents a homogeneous derivation of atmospheric parameters and iron abundances for a sample of giant and subgiant stars which host giant planets, as well as a control sample of subgiant stars not known to host giant planets. The analysis is done using the same technique as for our previous analysis of a large sample of planet-hosting and control sample dwarf stars. A comparison between the distributions of $[\text{Fe}/\text{H}]$ in planet-hosting main-sequence (MS) stars, subgiants, and giants within these samples finds that the MS stars and subgiants have the same mean metallicity of $\langle [\text{Fe}/\text{H}] \rangle \simeq +0.11$ dex, while the giant sample is typically more metal poor, having an average metallicity of $[\text{Fe}/\text{H}] = -0.06$ dex. The fact that the subgiants have the same average metallicities as the dwarfs indicates that significant accretion of solid metal-rich material onto the planet-hosting stars has not taken place, as such material would be diluted in the evolution from dwarf to subgiant. The lower metallicity found for the planet-hosting giant stars in comparison with the planet-hosting dwarfs and subgiants is interpreted as being related to the underlying stellar mass, with giants having larger masses and thus, on average, larger-mass protoplanetary disks. In core accretion models of planet formation, larger disk masses can contain the critical amount of metals necessary to form giant planets even at lower metallicities.

Key words: planetary systems – planets and satellites: formation – stars: abundances – stars: atmospheres – stars: fundamental parameters

Online-only material: color figures

1. INTRODUCTION

A physical property of planetary systems that has yet to be fully understood is a connection between planetary formation and the metallicities of the host stars. There is now unequivocal evidence that main-sequence (MS) FGK-type dwarfs known to have at least one giant planet (i.e., $M_p \sin i \geq 1 M_J$, where M_p is the minimum planetary mass, i is the inclination angle of the orbit, and M_J is a Jupiter mass) companion discovered via the radial velocity (RV) method are metal rich compared to similar stars in the disk field not known to harbor close-in giant planets (e.g., Santos et al. 2000, 2001, 2003, 2004; Fischer & Valenti 2005; Ghezzi et al. 2010). Contrary to this observation, there is increasing evidence that this planet–metallicity correlation does not extend to evolved giant stars; giants with planets tend to be more metal poor than their MS counterparts (e.g., Schuler et al. 2005; Pasquini et al. 2007).

The metallicity distribution of planetary host stars may hold critical clues to planet formation processes and the subsequent evolution of planetary systems. Indeed, the favored interpretation of the planet–metallicity correlation observed for MS dwarfs is that planets form more readily in high-metallicity environments (e.g., Fischer & Valenti 2005), in agreement with predictions of core accretion planet formation models (e.g., Ida & Lin 2004; Ercolano & Clarke 2010). A competing interpretation, however, holds that the enhanced metallicity results from the accretion of H-depleted rocky material onto the star and pollution of the thin convective envelopes of FGK dwarfs (e.g., Gonzalez 1997). This scenario would be supported by the lower metallicities of giants with planets, which having been enhanced

on the MS, would be diluted by the deepening convection zones as the stars evolve up the red giant branch (RGB).

An observational result that has been used as an argument in favor of the primordial enrichment hypothesis and against the pollution hypothesis is the observed metallicities of subgiants: subgiants with planetary companions have been shown to have enhanced metal abundances, similar to those of MS dwarfs with planets (Fischer & Valenti 2005). If the difference in metallicities of planet-hosting dwarfs and giants results from the pollution and subsequent dilution of the stars’ convective envelopes, one might expect the subgiants to have intermediate metallicities, forming a metallicity gradient from the metal-rich MS dwarfs, to the increasingly diluted subgiants, and finally to the fully diluted giants. Heretofore, this pattern has not been observed.

In this paper, we present the results of a homogeneous metallicity ($[\text{Fe}/\text{H}]$) analysis of 15 subgiants and 16 giants with planetary companions, as well as a control sample of 14 subgiants not known to harbor closely orbiting giant planets. This sample of evolved stars, which includes both giants and subgiants, constitutes the first to be analyzed in a homogeneous fashion within a single study. These metallicities are compared to those of a large sample of MS dwarfs with and without planets that have been derived as part of the same analysis and have been recently reported in Ghezzi et al. (2010, Paper I).

2. OBSERVATIONS

The sample of planet-hosting stars studied here contains 31 targets. The target list was compiled from the Extrasolar Planet Encyclopaedia,⁴ and these stars were originally part of the larger sample analyzed in Ghezzi et al. (2010); the latter study focused

* Based on observations made with the 2.2 m telescope at the European Southern Observatory (La Silla, Chile), under the agreement ESO-Observatório Nacional/MCT.

⁴ Available at <http://exoplanet.eu>.

Table 1
Log of Observations

Star	V	Observation Date	T_{exp} (s)	S/N ($\sim 6700 \text{ \AA}$)	Classification
Planet-hosting stars					
HD 5319	8.05	2007 Aug 28	1200	282	G
HD 10697	6.27	2007 Aug 29	200	277	SG
HD 11977	4.68	2007 Aug 30	80	344	G
HD 11964	6.42	2007 Aug 30	200	313	SG
HD 16400	5.65	2008 Aug 19	200	352	G
HD 23127	8.58	2007 Aug 30	1800	291	SG
HD 27442	4.44	2007 Oct 2	15	138	G
HD 28305	3.53	2007 Aug 30	30	291	G
HD 33283	8.05	2007 Aug 30	1200	385	SG
HD 38529	5.95	2007 Oct 2	200	314	SG
HD 47536	5.25	2007 Apr 8	80	369	G
HD 59686	5.45	2007 Apr 8	80	217	G
NGC 2423 3	10.04	2007 Aug 28	3000	183	G
HD 73526	8.99	2007 Apr 8	3000	301	SG
HD 88133	8.01	2007 Apr 7	1200	290	SG
NGC 4349 127	10.83	2008 Apr 6	10800	196	G
HD 117176	4.97	2007 Apr 6	80	415	SG
HD 122430	5.47	2007 Apr 6	80	199	G
HD 154857	7.24	2007 Apr 6	480	439	SG
HD 156846	6.50	2008 Apr 6	500	417	SG
HD 159868	7.24	2007 Apr 6	480	460	SG
HD 171028	8.31	2007 Aug 28	1200	331	SG
HD 175541	8.02	2007 Aug 28	1200	291	G
HD 177830	7.18	2007 Aug 29	480	207	SG
HD 188310	4.71	2008 Apr 6	100	344	G
HD 190647	7.78	2007 Aug 28	1200	363	SG
HD 192699	6.44	2007 Aug 28	200	259	G
HD 199665	5.51	2008 Apr 6	200	320	G
HD 210702	5.93	2007 Aug 28	200	280	G
HD 219449	4.24	2007 Aug 30	60	316	G
HD 224693	8.23	2007 Aug 29	1200	336	SG
Control sample					
HD 2151	2.82	2008 Aug 20	15	363	SG
HD 18907	5.88	2008 Aug 20	200	407	SG
HD 33473	6.75	2008 Aug 20	500	441	SG
HD 114613	4.85	2008 Feb 21	100	446	SG
HD 121384	6.00	2008 Apr 7	200	414	SG
HD 140785	7.38	2008 Apr 7	500	371	SG
HD 168060	7.34	2008 Aug 20	500	331	SG
HD 168723	3.23	2008 Aug 20	15	326	G
HD 188641	7.34	2008 Aug 19	500	409	SG
HD 196378	5.11	2008 Aug 19	100	433	SG
HD 205420	6.45	2008 Aug 19	200	307	SG
HD 208801	6.24	2008 Aug 19	200	301	SG
HD 212330	5.31	2008 Aug 20	100	273	SG
HD 219077	6.12	2008 Aug 19	200	372	SG
HD 221420	5.82	2008 Aug 20	200	307	SG

Note. SG: subgiant; G: giant.

on the analysis of dwarf stars, while the more evolved objects, giants, and subgiants are presented here. A sample of disk subgiants ($N = 14$) observed to not host closely orbiting giant planets was also observed with the same setup, and the target list was obtained from the list of candidates deemed to be “RV stable” from Fischer & Valenti (2005). The list with all stars analyzed in this study can be found in Table 1.

The observations consist of high-resolution spectra ($R = \lambda/\Delta\lambda \sim 48,000$) obtained with the FEROS spectrograph (Kaufer et al. 1999) attached to the MPG/ESO-2.20 m telescope (La

Silla, Chile).⁵ The spectra were reduced in a standard way. A more detailed account of the observations and the data reduction is provided in Paper I. A log of the observations with V magnitudes, observation dates, integration times, and signal-to-noise ratios (S/Ns) can be found in Table 1.

3. STELLAR PARAMETERS AND METALLICITIES

The derivation of stellar parameters and metallicities ($[\text{Fe}/\text{H}]$) in this study followed the same methodology presented

⁵ Under the agreement ESO-Observatório Nacional/MCT.

Table 2
Atmospheric Parameters and Metallicities

Star	T_{eff} (K)	$\log g$	ξ (km s ⁻¹)	A(Fe)	σ (Fe I)	N (Fe I)	σ (Fe II)	N (Fe II)	[Fe/H]
Planet-hosting stars									
HD 5319	4926	3.33	1.17	7.57	0.10	23	0.06	9	0.14
HD 10697	5677	4.06	1.28	7.57	0.08	27	0.05	12	0.14
HD 11977	4972	2.64	1.42	7.27	0.08	25	0.07	11	-0.16
HD 11964	5318	3.77	1.12	7.52	0.07	27	0.05	11	0.09
HD 16400	4783	2.39	1.46	7.36	0.11	25	0.09	7	-0.07
HD 23127	5769	4.01	1.30	7.77	0.09	27	0.06	10	0.34
HD 27442	4884	3.39	1.31	7.73	0.12	22	0.07	6	0.30
HD 28305	4963	2.87	1.68	7.60	0.13	25	0.07	7	0.17
HD 33283	5972	4.02	1.42	7.74	0.08	27	0.06	12	0.31
HD 38529	5558	3.62	1.32	7.76	0.09	26	0.06	10	0.33
HD 47536	4588	2.17	2.03	6.82	0.10	23	0.04	4	-0.61
HD 59686	4740	2.66	1.58	7.57	0.14	22	0.04	5	0.14
NGC 2423 3	4680	2.55	1.67	7.43	0.13	25	0.05	8	0.00
HD 73526	5571	3.89	1.15	7.64	0.07	26	0.05	10	0.21
HD 88133	5473	3.94	1.09	7.81	0.07	24	0.04	8	0.38
NGC 4349 127	4519	1.92	2.08	7.22	0.12	17	0.08	6	-0.21
HD 117176	5535	3.98	1.12	7.39	0.07	27	0.06	12	-0.04
HD 122430	4367	1.71	1.71	7.27	0.14	17	0.08	7	-0.16
HD 154857	5548	3.82	1.34	7.13	0.07	26	0.05	12	-0.30
HD 156846	5950	3.84	1.62	7.50	0.09	24	0.07	11	0.07
HD 159868	5572	3.90	1.21	7.36	0.06	26	0.06	12	-0.07
HD 171028	5681	3.88	1.71	6.87	0.06	24	0.06	10	-0.56
HD 175541	5022	3.19	1.15	7.27	0.05	24	0.06	11	-0.16
HD 177830	5054	3.83	1.30	7.84	0.11	20	0.05	6	0.41
HD 188310	4783	2.66	1.57	7.30	0.12	23	0.07	7	-0.13
HD 190647	5533	3.92	1.12	7.63	0.06	25	0.04	10	0.20
HD 192699	5086	3.18	1.17	7.20	0.07	25	0.06	11	-0.23
HD 199665	4948	2.69	1.31	7.34	0.09	24	0.09	8	-0.09
HD 210702	5028	3.40	1.24	7.52	0.09	26	0.05	7	0.09
HD 219449	4812	2.78	1.72	7.48	0.11	23	0.06	5	0.05
HD 224693	5902	3.97	1.36	7.66	0.10	27	0.06	12	0.23
Control sample									
HD 2151	5866	4.00	1.51	7.32	0.08	24	0.06	10	-0.11
HD 18907	5212	3.92	1.20	6.87	0.06	24	0.04	10	-0.56
HD 33473	5608	3.60	1.36	7.21	0.08	26	0.05	12	-0.22
HD 114613	5717	3.92	1.30	7.61	0.07	26	0.07	12	0.18
HD 121384	5249	3.67	1.24	6.93	0.07	27	0.05	12	-0.50
HD 140785	5723	3.98	1.18	7.40	0.05	23	0.04	12	-0.03
HD 168060	5577	3.93	1.14	7.72	0.09	27	0.04	10	0.29
HD 168723	4944	3.12	1.25	7.26	0.08	26	0.04	8	-0.17
HD 188641	5816	3.98	1.37	7.31	0.06	24	0.05	12	-0.12
HD 196378	5996	3.92	1.78	6.99	0.04	20	0.05	10	-0.44
HD 205420	6255	3.89	1.99	7.43	0.06	20	0.07	12	0.00
HD 208801	5061	3.80	1.08	7.59	0.08	21	0.06	8	0.16
HD 212330	5670	3.91	1.33	7.41	0.07	27	0.05	12	-0.02
HD 219077	5321	3.80	1.13	7.27	0.08	27	0.04	11	-0.16
HD 221420	5899	4.04	1.48	7.77	0.05	20	0.06	12	0.34

and discussed in Paper I. The same selection of Fe I and Fe II lines was analyzed and their equivalent widths were also measured using the automatic code of equivalent width measurement ARES (Sousa et al. 2007). In order to further test the quality of automatic equivalent width measurements for the parameter space covered by this particular set of subgiant and giant stars, equivalent widths of two sample targets HD 188310 (with T_{eff} typical of the giants in our sample and a spectrum with high S/N) and HD 27442 (typical T_{eff} but with a lower S/N spectrum) were measured manually (using the task `sp1ot` on IRAF). Our results indicate that equivalent widths measured with IRAF compare favorably with the automatic ones: $\langle \text{EW}_{\text{ARES}} - \text{EW}_{\text{Manual}} \rangle = -0.43 \pm 2.28 \text{ m\AA}$ for HD 188310 and $+0.15 \pm 3.42 \text{ m\AA}$ for

HD 27442, which is consistent with previous results in Sousa et al. (2007).

Effective temperatures, surface gravities, microturbulent velocities, and iron abundances were derived under the assumption of LTE and self-consistently from the requirement that the iron abundance be independent of the line excitation potential and measured equivalent widths, as well as from the forced agreement between Fe I and Fe II abundances. Although this analysis uses the approximation of LTE, a discussion of possible non-LTE effects in the Fe abundances will be presented in Section 4.1.3. Table 2 lists the derived stellar parameters for the target stars. The number of Fe I and Fe II lines (and the standard deviations in each case) for each star is also listed.

Uncertainties in the derived parameters T_{eff} , $\log g$, ξ , and $[\text{Fe}/\text{H}]$ can be estimated as in González & Vanture (1998), similarly to Paper I. The typical values for the internal errors in this study are ~ 50 K in T_{eff} , 0.15 dex in $\log g$, 0.05 km s^{-1} for ξ , and 0.05 dex in $[\text{Fe}/\text{H}]$. (See Paper I for a discussion of these internal uncertainties). We note, however, that the real uncertainties are expected to be somewhat larger (100 K in T_{eff} , 0.20 dex in $\log g$, 0.20 km s^{-1} in ξ , and 0.10 dex in $[\text{Fe}/\text{H}]$) than the internal errors. The sensitivity of Fe I abundances to changes in the parameters T_{eff} , $\log g$, and ξ is also investigated. For this exercise, we use the subgiant HD 11964 ($T_{\text{eff}} = 5318$ K) and two giants that span the T_{eff} interval of most of the giant sample: HD 11977 ($T_{\text{eff}} = 4972$ K), NGC 2423 3 ($T_{\text{eff}} = 4680$ K). A variation of ± 100 K in T_{eff} induces a change of ± 0.05 and ± 0.08 dex in $A(\text{Fe I})$ for the coolest (NGC 24233) and hottest (HD 11977) giants, respectively. For the subgiant, the sensitivity is ± 0.08 dex. A variation of ± 0.2 dex in $\log g$ does not affect significantly the Fe abundances: $A(\text{Fe})$ changes by ~ 0.01 dex for the hotter stars and ~ 0.03 dex for the cooler star. As expected, a decrease in the microturbulence causes an increase in $A(\text{Fe I})$; for the subgiant star, a change of $\pm 0.20 \text{ km s}^{-1}$ causes a variation of ∓ 0.08 dex in the Fe I abundance, while for the giants, this variation is around ∓ 0.10 . The total errors in $A(\text{Fe})$ from these typical uncertainties are ± 0.11 dex for the subgiants and ± 0.13 dex for the giants. As the results in this study for the giants and subgiants will be compared to those for the dwarfs in Paper I, we repeat the above exercise for a typical dwarf with solar parameters (HD 106252; Paper I). Variations of ± 100 K in T_{eff} , ± 0.20 dex in $\log g$, and $\pm 0.20 \text{ km s}^{-1}$ in ξ cause changes of, respectively, ± 0.08 , ≤ 0.01 , and ∓ 0.05 dex in $A(\text{Fe I})$, or a total error of ± 0.1 dex. These total uncertainties for the dwarfs in Paper I are slightly lower but not significantly different from the total uncertainties estimated for the subgiants (0.11 dex) and giants (0.13 dex).

The derived effective temperatures for the stars in our sample can be compared with independent results from photometric $V - K$ calibrations. Several photometric calibrations are available in the literature (e.g., Alonso et al. 1999; Ramírez & Meléndez 2005). González Hernández & Bonifacio (2009) presented a new implementation of the infrared flux method using Two Micron All Sky Survey (2MASS) magnitudes and Kurucz models. A comparison of the derived spectroscopic effective temperatures with photometric T_{eff} s derived from the $V - K$ calibration by González Hernández & Bonifacio (2009) is shown in the top panel of Figure 1. Results are shown for all stars in our sample which have unsaturated K_s 2MASS magnitudes (with errors in $K_s < 0.1$ mag); reddening corrections from Arenou et al. (1992) were applied to obtain the de-reddened colors. The comparison between the two scales is quite good for the entire T_{eff} range, with agreement for most of the stars within ± 100 K (shown as the dashed lines in the figure). There is not a significant systematic difference in the effective temperatures between giants and subgiants, but we note a few outliers falling above the dashed lines (mostly subgiants) and two results for subgiants which fall below. The average difference between the two scales is well within the expected errors and overall agrees with the variations typically found between different T_{eff} scales in the literature: $\langle \delta T_{\text{eff}} (\text{This Study} - \text{González Hernández \& Bonifacio 2009}) \rangle = -48 \pm 136$ K.

The more recent calibration by Casagrande et al. (2010) is hotter than that of González Hernández & Bonifacio (2009); a comparison with our results for the subgiants (the calibration of Casagrande et al. 2010 only applies for dwarfs and subgiants)

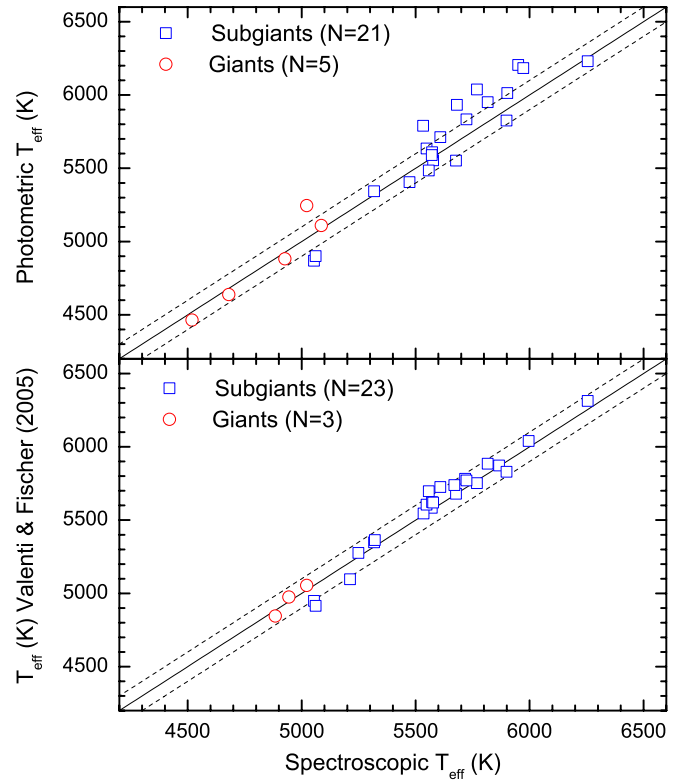


Figure 1. Top panel: comparison between the spectroscopic effective temperatures derived in this study with T_{eff} s derived from the $V - K$ calibration by González Hernández & Bonifacio (2009). Subgiants are the open blue squares and giants are the open red circles. Bottom panel: comparison between effective temperatures derived in this study and those obtained by Valenti & Fischer (2005) for stars in common. The solid line represents perfect agreement and the dashed lines ± 100 K. The three effective temperature scales shown in the top and bottom panels show good agreement within the expected errors in the determinations.

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

shows a larger systematic difference of $\langle \delta T_{\text{eff}} (\text{This Study} - \text{Casagrande et al. 2010}) \rangle_{\text{subgiants}} = -106 \pm 147$ K. For the calibration of González Hernández & Bonifacio (2009), we find $\langle \delta T_{\text{eff}} (\text{This Study} - \text{González Hernández \& Bonifacio 2009}) \rangle_{\text{subgiants}} = -55 \pm 142$ K. This difference of ~ 50 K is consistent with the discussion presented in Section 2.5 of Casagrande et al. (2010). Reddening corrections applied to $(V - K)$ also influence the derived photometric temperatures: a change of 0.01 mag in $E(B - V)$ can lead to a change of 50 K in the effective temperature (Casagrande et al. 2010). Note that Casagrande et al. (2010) have not adopted reddening corrections for stars in their samples closer than ~ 75 pc. If we also neglect reddening corrections for those stars in our sample which are closer than ~ 75 pc and recompute the photometric T_{eff} s, the average differences become $\langle \delta T_{\text{eff}} (\text{This Study} - \text{Casagrande et al. 2010}) \rangle_{\text{subgiants}} = -33 \pm 144$ K.

The bottom panel of Figure 1 shows the comparison of our derived effective temperatures with those obtained by Valenti & Fischer (2005); the latter study also derived T_{eff} spectroscopically, although their analysis followed a different method which consisted in fitting the observed spectra by adjusting 41 free parameters (one of them being the effective temperature). The T_{eff} results in the two spectroscopic analyses agree well: $\langle \delta T_{\text{eff}} (\text{This Study} - \text{Valenti \& Fischer 2005}) \rangle = -18 \pm 67$ K.

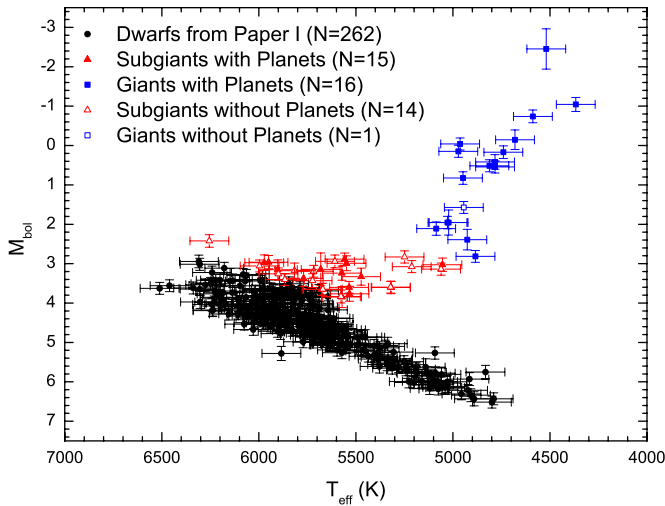


Figure 2. Location of studied stars in an H-R diagram. The targets analyzed in this study are evolved away from the MS. The samples are segregated in dwarfs (black circles; analyzed in Paper I), subgiants (red triangles), and giants (blue squares). All giant stars in our sample, except one, host giant planets; the sample of subgiants include both planet-hosting stars as well as a control sample of subgiant stars not known to host giant planets.

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

3.1. Evolutionary Parameters

As mentioned previously, Paper I analyzed unevolved stars with and without planets, while the present study focuses on more evolved stars, also both with and without giant planets. Figure 2 shows the location of the sample stars in an H-R diagram with the bolometric magnitudes versus effective temperatures. The bolometric magnitudes for the stars were calculated using the bolometric corrections of Girardi et al. (2002, see details in Paper I). This figure also includes for comparison the sample of stars which was studied in Paper I (represented by black filled circles), and these generally define the location of the MS. The target stars analyzed here are obviously more evolved. In this study, a star is classified as a subgiant (represented as red triangles in Figure 2) if it is 1.5 mag above the lower boundary of the MS and has $M_{\text{bol}} > 2.82$; the 17 stars which have $M_{\text{bol}} < 2.82$ are classified as giants (represented as blue squares in Figure 2). This boundary transition between the MS and the subgiant branch is somewhat uncertain and for two stars in particular we adopted a different classification: HD 2151 was classified as a subgiant (although it is not 1.5 mag above the lower boundary of the MS) because of its low derived values of $\log g$ (~ 4.0), and HD 205420 (the isolated star with $T_{\text{eff}} = 6255$ K and $M_{\text{bol}} < 2.82$) is considered as a subgiant. The transition between the subgiant and giant branches is also uncertain. In particular, the classification of two stars (HD 177830 and HD 208801) which lie close to the base of the RGB is uncertain; however, their derived surface gravities are more compatible with their classification as subgiants. (Nevertheless, the implications of including these stars as giants in our analysis is discussed in Section 4.1.2.) The adopted classification of the sample stars in giants and subgiants can be found in the last column of Table 1.

Table 3 summarizes the evolutionary parameters calculated for the studied stars. The parallaxes are from the *Hipparcos* catalog; the luminosities are calculated using the parallax, V magnitudes, reddening, and the derived effective temperatures (see Paper I for details). Three stars (namely, NGC 2423 3,

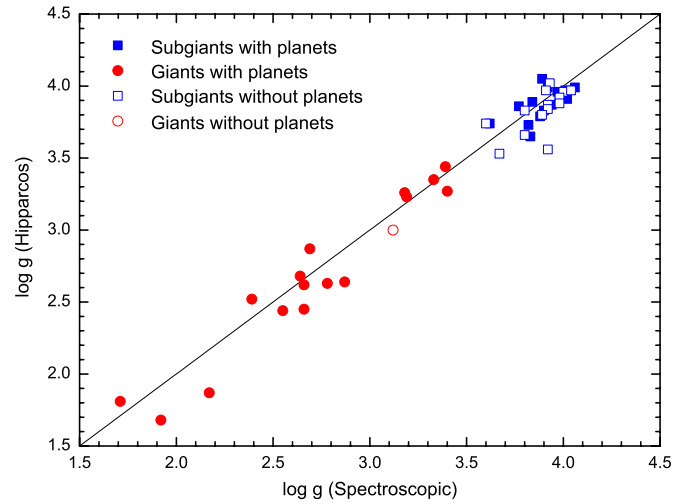


Figure 3. Comparison between the spectroscopic gravities derived in this study with those derived using *Hipparcos* parallaxes. The agreement between the two scales is good with no significant offsets. Perfect agreement is represented by the solid line.

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

NGC 4349 127, and HD 171028) were not present in the *Hipparcos* catalog, thus their V magnitudes and parallaxes come from the references in the Extrasolar Planet Encyclopaedia. Note also that the Arenou et al. (1992) model for reddening is accurate to distances within 1 kpc of the Sun. The radii, masses, as well as *Hipparcos* gravities and estimated ages in Table 3 were calculated using L. Girardi's web code PARAM,⁶ which is based on a Bayesian parameter estimation method (da Silva et al. 2006). We note that the Y^2 evolutionary tracks (Yi et al. 2003) were not used in this paper because these do not follow evolution through the red clump.

The surface gravity values obtained here from the ionization equilibrium of Fe I and Fe II and in LTE (Column 3; Table 2) can be compared with gravities which are based on *Hipparcos* parallaxes (Column 11; Table 3); such a comparison is shown in Figure 3. The agreement between the average values for the two scales is found to be good: $\langle \delta (\log g_{\text{Hipparcos}} - \log g_{\text{This Study}}) \rangle = -0.04 \pm 0.12$ dex. Such an agreement between the *Hipparcos* gravities and spectroscopic values derived from the agreement between Fe I and Fe II suggest the absence of strong non-LTE effects (see discussion in Section 4.1.3).

Concerning their masses and ages, the sample of giants studied here is more massive and younger than the subgiants and dwarfs (from Paper I). The giants in our sample have an average mass of $1.82 \pm 0.68 M_{\odot}$ and a distribution ranging between ~ 1.1 and $3.8 M_{\odot}$; their average age is $\langle \text{Age} \rangle_{\text{giants}} = 2.22 \pm 1.37$ Gyr. For comparison we note that the sample dwarfs (Paper I) have $\langle M \rangle_{\text{dwarfs}} = 1.03 \pm 0.17 M_{\odot}$ (encompassing the interval ~ 0.6 – $1.4 M_{\odot}$) and $\langle \text{Age} \rangle_{\text{dwarfs}} = 5.34 \pm 2.70$ Gyr. The overlap in the mass range between the samples of giants and dwarfs is therefore small. We note that the masses and ages of the dwarfs were derived in a different way (Y^2 evolutionary tracks and isochrones). However, it was shown in Paper I that the results from the two methods are consistent for dwarfs: $\Delta M (Y^2 - \text{Girardi's Code}) = 0.03 \pm 0.05 M_{\odot}$ and $\Delta \text{Age} (Y^2 - \text{Girardi's Code}) = 0.37 \pm 1.46$ Gyr (see the last paragraph of Section 3.4 in Paper I).

⁶ Available at <http://stev.oapd.inaf.it/cgi-bin/param>.

Table 3
Evolutionary Parameters

Star	π (mas)	σ_π (mas)	A_V (mag)	$\log(L/L_\odot)$	$\sigma_{\log(L/L_\odot)}$	R (R_\odot)	σ_R (R_\odot)	M (M_\odot)	$\sigma(M)$ (M_\odot)	$\log g_{\text{Hipp}}$	$\sigma(\log g_{\text{Hipp}})$	Age (Gyr)	$\sigma(\text{Age})$ (Gyr)
Planet-hosting stars													
HD 5319	8.74	0.86	0.10	0.952	0.105	3.97	0.43	1.40	0.14	3.35	0.10	3.30	1.11
HD 10697	30.70	0.43	0.00	0.446	0.061	1.69	0.06	1.11	0.03	3.99	0.03	6.75	0.71
HD 11977	14.91	0.16	0.16	1.849	0.061	11.04	0.43	2.27	0.29	2.68	0.07	0.83	0.27
HD 11964	30.44	0.60	0.10	0.466	0.062	1.97	0.08	1.12	0.03	3.86	0.03	7.02	0.67
HD 16400	10.81	0.45	0.08	1.741	0.074	10.50	0.45	1.43	0.31	2.52	0.11	2.66	1.46
HD 23127	10.13	0.67	0.21	0.559	0.083	1.81	0.13	1.21	0.05	3.97	0.06	4.66	0.81
HD 27442	54.83	0.15	0.03	0.782	0.060	3.50	0.15	1.35	0.08	3.44	0.06	3.79	0.85
HD 28305	22.24	0.25	0.06	1.924	0.061	12.69	0.46	2.75	0.11	2.64	0.03	0.51	0.09
HD 33283	10.62	0.62	0.21	0.718	0.079	2.08	0.13	1.39	0.06	3.91	0.05	2.93	0.41
HD 38529	25.46	0.40	0.03	0.754	0.062	2.49	0.10	1.37	0.02	3.74	0.03	3.35	0.14
HD 47536	8.11	0.23	0.11	2.204	0.065	19.84	1.09	1.15	0.25	1.87	0.12	4.38	2.58
HD 59686	10.32	0.28	0.00	1.840	0.064	11.80	0.60	2.27	0.30	2.62	0.09	0.92	0.33
NGC 2423 3	1.31	0.03	0.39	1.966	0.099	14.11	0.88	2.16	0.38	2.44	0.11	0.96	0.40
HD 73526	9.93	1.01	0.06	0.369	0.107	1.53	0.16	1.05	0.05	4.05	0.08	8.50	1.34
HD 88133	12.28	0.88	0.04	0.576	0.087	2.04	0.15	1.20	0.06	3.87	0.04	5.22	0.90
NGC 4349 127	0.45	0.01	1.08	2.889	0.205	44.72	2.46	3.77	0.36	1.68	0.07	0.20	0.05
HD 117176	55.60	0.24	0.01	0.467	0.060	1.83	0.06	1.08	0.03	3.91	0.03	7.83	0.63
HD 122430	7.42	0.33	0.28	2.325	0.071	24.49	1.78	1.53	0.31	1.81	0.12	2.18	1.11
HD 154857	15.57	0.71	0.12	0.712	0.075	2.40	0.14	1.21	0.06	3.73	0.04	4.43	0.63
HD 156846	21.00	0.51	0.14	0.724	0.067	2.11	0.08	1.36	0.06	3.89	0.04	3.17	0.47
HD 159868	17.04	0.76	0.08	0.612	0.072	2.11	0.11	1.19	0.04	3.83	0.04	5.31	0.76
HD 171028	11.10	1.85	0.31	0.651	0.165	2.06	0.28	1.03	0.09	3.79	0.08	7.25	2.44
HD 175541	7.87	0.95	0.32	1.126	0.127	4.55	0.57	1.37	0.16	3.23	0.11	3.11	1.16
HD 177830	16.94	0.63	0.08	0.698	0.068	2.85	0.16	1.41	0.03	3.65	0.04	3.14	0.20
HD 188310	17.77	0.29	0.09	1.690	0.062	10.23	0.39	1.16	0.28	2.45	0.11	4.63	2.88
HD 190647	17.46	0.81	0.15	0.402	0.076	1.68	0.09	1.07	0.03	3.99	0.04	7.96	0.81
HD 192699	15.24	0.57	0.04	1.064	0.068	4.41	0.23	1.38	0.13	3.26	0.07	2.90	0.88
HD 199665	13.28	0.31	0.05	1.578	0.063	8.29	0.31	2.01	0.10	2.87	0.04	1.10	0.16
HD 210702	18.20	0.39	0.05	1.125	0.063	4.83	0.24	1.72	0.13	3.27	0.06	1.68	0.36
HD 219449	21.77	0.29	0.10	1.702	0.061	10.16	0.45	1.74	0.35	2.63	0.11	1.69	0.81
HD 224693	10.16	0.91	0.10	0.646	0.101	1.90	0.17	1.30	0.08	3.96	0.06	3.54	0.68
Control sample													
HD 2151	134.07	0.11	0.02	0.547	0.060	1.77	0.05	1.13	0.04	3.96	0.03	6.13	0.88
HD 18907	31.06	0.36	0.09	0.678	0.061	2.66	0.10	1.02	0.06	3.56	0.05	7.62	1.51
HD 33473	18.69	0.49	0.09	0.731	0.064	2.41	0.10	1.25	0.04	3.74	0.03	4.06	0.37
HD 114613	48.38	0.29	0.04	0.631	0.060	2.06	0.07	1.26	0.03	3.87	0.03	4.22	0.27
HD 121384	25.84	0.48	0.07	0.776	0.062	2.95	0.12	1.15	0.08	3.53	0.06	4.90	1.21
HD 140785	17.54	0.56	0.12	0.536	0.070	1.85	0.08	1.13	0.03	3.92	0.04	6.33	0.75
HD 168060	21.07	0.65	0.06	0.375	0.066	1.61	0.07	1.07	0.02	4.02	0.04	7.92	0.56
HD 168723	53.93	0.18	0.06	1.279	0.060	6.00	0.24	1.41	0.16	3.00	0.07	2.81	1.01
HD 188641	16.14	0.82	0.16	0.637	0.078	1.98	0.12	1.18	0.04	3.88	0.04	5.30	0.75
HD 196378	40.55	0.27	0.05	0.684	0.060	2.01	0.06	1.10	0.03	3.84	0.03	5.62	0.43
HD 205420	15.81	0.39	0.04	0.939	0.064	2.47	0.09	1.53	0.05	3.80	0.03	2.09	0.22
HD 208801	27.11	0.41	0.05	0.653	0.061	2.73	0.13	1.34	0.05	3.66	0.04	3.61	0.41
HD 212330	48.63	0.34	0.04	0.449	0.060	1.71	0.06	1.07	0.03	3.97	0.03	7.78	0.80
HD 219077	34.07	0.37	0.05	0.470	0.061	1.99	0.08	1.06	0.04	3.83	0.03	8.27	0.70
HD 221420	31.81	0.27	0.07	0.605	0.060	1.88	0.05	1.31	0.04	3.97	0.03	3.43	0.47

In terms of their average masses, the sample of subgiants studied here falls technically in between the sample of giants and dwarfs, but there is considerable overlap with the mass range of the dwarf sample (the subgiant sample encompasses the interval $\sim 1.0\text{--}1.5 M_\odot$, with an average mass of $1.20 \pm 0.14 M_\odot$). It is interesting to note that the subgiants in our sample are on average slightly older than the dwarfs ($\langle \text{Age} \rangle_{\text{subgiants}} = 5.46 \pm 1.92$ Gyr), representing the oldest population in this study. In summary, the sample subgiants are a more evolved population of the previously studied dwarfs from Paper I as these dwarfs and subgiants have approximately the same mass ranges. The sample giants, however, are evolved from stars which are more massive and are on average the youngest of all target stars.

4. DISCUSSION

4.1. Metallicity Distributions of Evolved Stars Hosting Planets

As the number of discovered planet-hosting stars increases and samples include a larger number of stars which are on the RGB, metallicity distributions of evolved stars hosting planets have started to appear in the literature. Because the samples are still relatively small, and the abundance analyses are not always homogeneous, there is some controversy in some of the conclusions of recent studies of giants, which are briefly summarized as follows. Schuler et al. (2005) compared the iron abundances of seven giants with planets known at the time and found that their metallicity distribution was on average

lower than that of dwarfs with planets. This result was later confirmed by Pasquini et al. (2007), who concluded that the metallicity distributions of giants with planets do not favor metal-rich systems. Their results were based on a sample of 14 giants with planets (10 of which analyzed by their group) and are interpreted as possible evidence for pollution. Hekker & Meléndez (2007) analyzed 380 G-K giants as part of the RV survey at Lick Observatory. Five of these stars host planets; they also gather abundances from the literature for another 15 giants and obtain an average metallicity for the sample of -0.05 dex. In addition, this study concludes that there is an offset of 0.13 dex between the metallicity distributions of giants with and without planets; the latter are found to be generally more metal poor. Such an offset in the metallicity distributions is not confirmed in the recent study by Takeda et al. (2008), who analyzed a sample of 322 intermediate-mass late-G giants; 10 of these stars host planets. Their comparisons between the metallicity distributions of giants with and without detected planets reveal no significant difference between the two samples; both distributions have average metallicities around -0.12 dex. In the following sections we discuss the metallicity distributions for the giant and subgiant planet-hosting stars in our sample.

4.1.1. Giants

The iron abundance distribution derived from the sample of giant stars hosting planets ($N = 16$) is shown in the top panel of Figure 4 as a red dotted line histogram; the average value for this distribution is $\langle [\text{Fe}/\text{H}] \rangle_{\text{giants}} = -0.06$ dex. For comparison, the iron abundances obtained for the sample of dwarf stars hosting giant planets ($N = 117$) from Paper I are also shown (black solid line histogram). It is apparent from the figure that the metallicity distribution of the giant stars peaks at a lower metallicity value when compared to the dwarf stars; the difference between the average $[\text{Fe}/\text{H}]$ is 0.17 dex. The application of a Kolmogorov–Smirnov (K-S) test gives a probability of only 1% that the MS dwarfs and giants are drawn from the same parent Fe-abundance population. It is important to recognize, however, the relatively small number of giant stars in this comparison, although this contains $\sim 45\%$ of the total number of giant stars hosting giant planets found to date.

In order to improve the giant star statistics as much as possible, iron abundances for the remaining giants known to have planets were collected from different studies in the literature; their metallicities are listed in Table 4. Literature results for the giant star sample studied here are also presented for comparison. The histogram in the bottom panel of Figure 4 shows the metallicity distribution for the sample including both the giants in this study and for all other literature giants in Table 4 ($N = 37$; blue dashed line). The metallicity distribution for the planet-hosting dwarfs from Paper I is shown again for comparison. Using the extended giant sample yields a similar conclusion: the metallicities of giant stars with planets are on average lower than dwarfs with planets. In particular, the average metallicity for the extended sample (giants from this study plus literature) is somewhat lower ($\langle [\text{Fe}/\text{H}] \rangle = -0.12$ dex), but not significantly so, than the average metallicity obtained using only the giants from this study by 0.06 dex. The results from this extended giant sample reinforce the premise that giant stars with giant planets seem to have on average lower iron abundances than dwarf stars with giant planets. The application of a K-S test using the extended giant sample gives a very small probability of 1.91×10^{-5} that the MS dwarfs and giants are drawn from the same parent population. Such results are in line with the

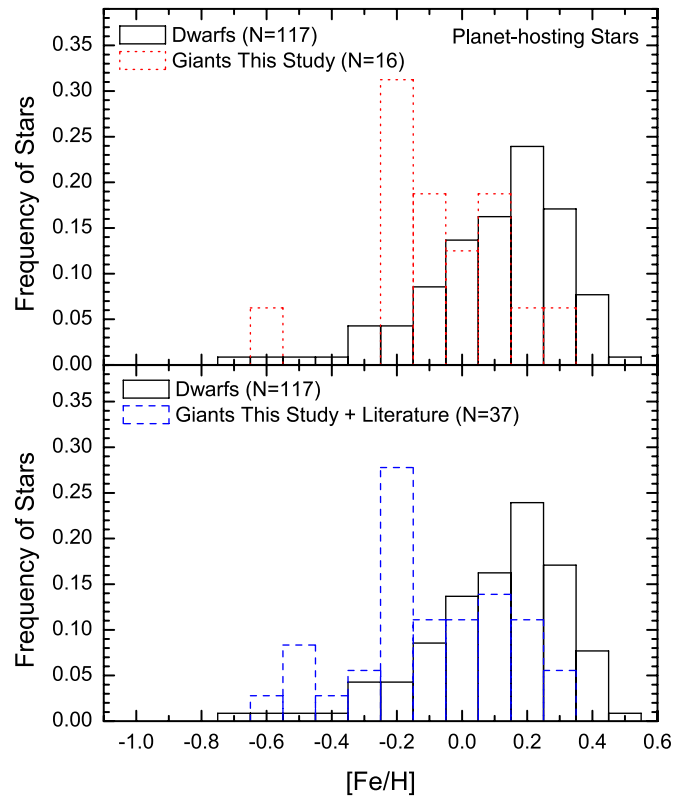


Figure 4. Top panel: metallicity distributions obtained for planet-hosting dwarfs (black solid line) and giants (red dotted line). All abundance results in these distributions were derived homogeneously. Bottom panel: metallicity distributions for planet-hosting dwarfs (black solid line; same as top panel), and all giant star hosting giant planets known to date (blue dashed line). The metallicities for those planet-hosting giants not analyzed in this study are taken as the average of the iron abundance values found in the literature (see Table 4). (A color version of this figure is available in the online journal.)

conclusions by Pasquini et al. (2007, see also Schuler et al. 2005) who discuss that the metallicity distributions of planet-hosting dwarfs and giants are different; with the giant stars having a distribution shifted to lower metallicities by 0.2–0.3 dex with respect to the dwarfs.

As a final note, we recall the discussion about uncertainties in Section 3. Our spectroscopic temperatures for the giants would be ~ 20 K cooler if we considered the photometric temperatures as the “correct” scale. This would result in underestimated Fe I abundances by 0.02 dex at most. The sensitivity of this parameter to T_{eff} , $\log g$, and ξ was also discussed and the conclusion was that systematic effects of order of 0.1 dex can exist when comparing abundances of dwarfs and giants. Comparisons of our metallicities with those from many studies in the literature (see Table 5 of Paper I and Table 4 of this study) do not show evidence for these possible systematic effects in our metallicities. Even if they existed, neither would be sufficient to explain the differences of 0.17–0.23 dex found between the average metallicities of dwarfs and giants.

4.1.2. Subgiants

An additional important aspect of the present study is the homogeneous abundance analysis for samples of subgiants with and without giant planets. A comparison of the metallicity distributions for the two samples (Figure 5, top panel) points to a similarity to that found for dwarfs, namely, that subgiant stars without planets are on average more metal poor than the

Table 4
Metallicities of Giant Stars

Star	[Fe/H]	Reference
Giants in this study		
HD 5319	0.14	This study
	0.15	Valenti & Fischer (2005)
HD 11977	−0.16	This study
	−0.21	da Silva et al. (2006)
	−0.09	Sousa et al. (2006)
	−0.07	This study
HD 16400	−0.06	Takeda et al. (2008)
	0.30	This study
HD 27442	0.42	Santos et al. (2003)
	0.42	Valenti & Fischer (2005)
	0.17	This study
HD 28305	0.11	Mishenina et al. (2006)
	0.20	Schuler et al. (2006)
	0.17	Sato et al. (2007)
	0.05	Hekker & Meléndez (2007)
	0.13	Takeda et al. (2008)
HD 47536	−0.61	This study
	−0.54	Santos et al. (2004)
	−0.54	Sadakane et al. (2005)
	−0.68	da Silva et al. (2006)
HD 59686	0.14	This study
	0.28	Santos et al. (2005)
	0.11	Sadakane et al. (2005)
	0.02	Mishenina et al. (2006)
	0.15	Hekker & Meléndez (2007)
NGC 2423 3	0.00	This study
	0.00	Santos et al. (2009)
NGC 4349 127	−0.21	This study
	−0.14	Santos et al. (2009)
	−0.16	This study
HD 122430	−0.05	da Silva et al. (2006)
	−0.16	This study
HD 175541	−0.07	Valenti & Fischer (2005)
	−0.07	Johnson et al. (2007)
	−0.13	This study
HD 188310	−0.21	Sato et al. (2008a)
	−0.18	Takeda et al. (2008)
HD 192699	−0.23	This study
	−0.15	Johnson et al. (2007)
HD 199665	−0.09	This study
	−0.05	Sato et al. (2008a)
	−0.05	Takeda et al. (2008)
HD 210702	0.09	This study
	0.06	Luck & Heiter (2007)
	+0.12	Johnson et al. (2007)
HD 219449	0.05	This study
	0.05	Santos et al. (2005)
	0.09	Sadakane et al. (2005)
	0.05	Luck & Heiter (2007)
	−0.03	Hekker & Meléndez (2007)
Giants from the Literature		
HD 13189	−0.58	Schuler et al. (2005)
	−0.39	Sousa et al. (2006)
	−0.49	Average
HD 17092	0.22	Niedzielski et al. (2007)
HD 32518	−0.15	Döllinger et al. (2009a)
HD 62509	0.05	Sadakane et al. (2005)
	0.19	Hatzes et al. (2006)
	0.17	Luck & Heiter (2007)
	0.07	Hekker & Meléndez (2007)
	0.12	Average
4 UMa	−0.16	Luck & Heiter (2007)
	−0.25	Döllinger et al. (2007)
	−0.21	Average

Table 4
(Continued)

Star	[Fe/H]	Reference
HD 81688	−0.36	Sato et al. (2008a)
BD+20 2457	−1.00	Niedzielski et al. (2009b)
gamma 1 Leo	−0.49	McWilliam (1990)
	−0.51	Han et al. (2010)
	−0.50	Average
HD 102272	−0.26	Niedzielski et al. (2009a)
HD 104985	−0.35	Sato et al. (2003)
	−0.28	Santos et al. (2005)
	−0.15	Takeda et al. (2005)
	−0.26	Luck & Heiter (2007)
	−0.26	Average
HD 110014	0.19	da Silva et al. (2006)
11 UMi	0.04	Döllinger et al. (2009a)
HIP 75458	0.03	McWilliam (1990)
	0.09	Santos et al. (2003)
	0.13	Santos et al. (2004)
	0.12	Sadakane et al. (2005)
	0.11	Hekker & Meléndez (2007)
HD 139357	0.10	Average
	−0.13	Döllinger et al. (2009b)
42 Dra	−0.46	Döllinger et al. (2009b)
HD 173416	−0.22	Liu et al. (2009)
HD 180902	0.04	Johnson et al. (2010b)
HD 181342	0.26	Johnson et al. (2010b)
HD 240210	−0.18	Niedzielski et al. (2009b)
14 And	−0.24	Sato et al. (2008b)
HD 222404	+0.18	Fuhrmann (2004)
	+0.16	Santos et al. (2004)
	+0.17	Average

sample of subgiants hosting planets. The results from Paper I showed that the metallicity distribution of dwarfs hosting planets was more metal rich by 0.15 dex than that for dwarfs not hosting planets. This abundance offset found previously for unevolved stars compares well with the difference obtained here for subgiants: the average metallicity for our sample of subgiants hosting planets ($N = 15$) is $\langle [\text{Fe}/\text{H}] \rangle = +0.12$ dex and for subgiants without planets ($N = 14$) it is more metal poor by 0.21 dex ($\langle [\text{Fe}/\text{H}] \rangle = -0.09$ dex). Fischer & Valenti (2005) also analyzed a sample of 86 subgiants, 9 of which host giant planets. They find that the median metallicity of their sample of subgiants without detected planets is -0.01 dex, while that of the sample of subgiants with planets is $+0.35$ dex. This is more metal rich than the results found here for planet-hosting subgiants: the median metallicity of the subgiant distribution obtained here is 0.20 dex.

As discussed in the previous section, the sample of subgiants studied here is in fact on average older than the sample of dwarfs (from Paper I), as well as the giant star sample. In terms of their mass distribution the subgiants, although including a few more massive stars, constitute the same general population as the dwarfs, but are just older and more evolved. A comparison of the metallicities of subgiants in our sample and dwarfs from Paper I is shown in Figure 5 (bottom panel), and the distributions are not significantly different. A K-S test gives a probability of 56% that the two samples belong to the same parent population. Based on a K-S test applied to their samples, Fischer & Valenti (2005) also find that the metallicity distributions of MS and subgiant stars with planets are consistent, and that both samples are more metal rich than their counterparts without detected planets.

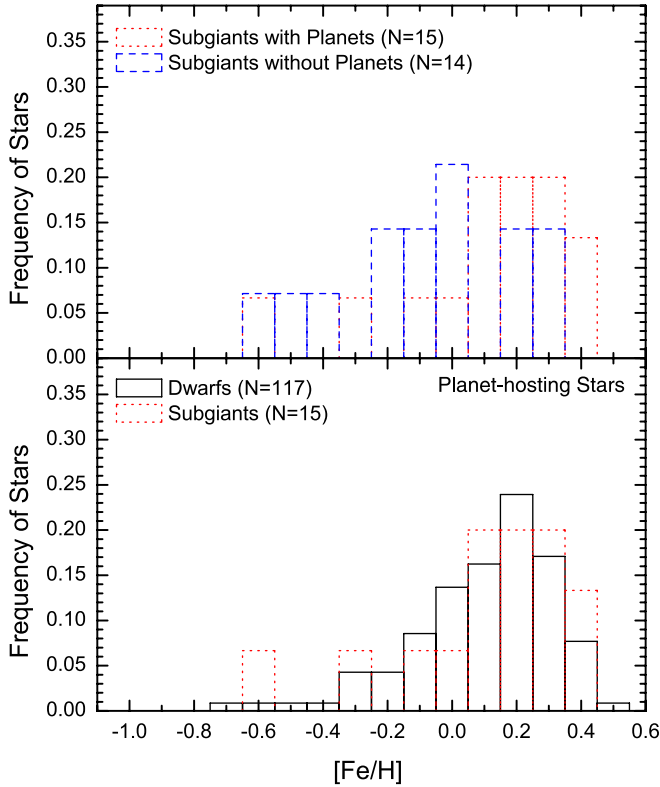


Figure 5. Top panel: metallicity distributions obtained for the sample of subgiant stars hosting planets (red dotted line histogram) and the control sample of subgiants not known to have giant planets (blue dashed line histogram). The planet-hosting stars are found to be on average more metal rich than the control sample by 0.21 dex. Bottom panel: metallicity distributions of subgiant stars with planets (red dotted line histogram) in comparison with the dwarf star planet-hosting sample (black solid line histogram) analyzed in Paper I. The two distributions are similar with no obvious abundance shifts.

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

There is presently a negligible offset (0.01 dex) between the averages of the metallicity distributions of dwarfs with planets (from Paper I) and the subgiants with planets studied here: both have $\langle [\text{Fe}/\text{H}] \rangle \simeq +0.11$ dex. In general terms, this is what would be expected if dwarfs and subgiants come from the same population and if there are no effects related to age–metallicity. It should be recognized, however, that the subgiant sample is significantly smaller than the dwarf sample and that this offset in metallicity, which is found to be zero for the stars with planets, could in fact be as large as ~ 0.05 dex given the uncertainties in the analysis and the small number statistics. In fact, there is a small offset of 0.05 dex between the averages of the metallicity distributions of dwarfs and subgiants without planets (with the latter being more metal poor). For example, if the planet-hosting star (HD 177830) which lies in the transition between the subgiant and red giant branches (previously noted in Section 3.1; Figure 2) is instead classified as a giant (as in Hekker & Meléndez 2007), this will affect the average metallicity of the sample of subgiants with planets which will change to a slightly lower value: $\langle [\text{Fe}/\text{H}] \rangle = +0.10$ dex ($N = 14$); or an offset between subgiants and dwarfs with planets of 0.01 dex (note also that in this case the giants will have an average metallicity which is slightly higher of $\langle [\text{Fe}/\text{H}] \rangle = -0.03$ dex). If this offset in the metallicities between the dwarfs and subgiants is small but real, a possible interpretation for the lower metallicity found for the subgiants is that these small differences in the abundances are the result

of chemical evolution; since the sample subgiant stars are older they would be on average slightly more metal poor.

We note that the discussion about uncertainties presented in Section 3 revealed that no significant systematic effects should be expected in the comparison of metallicities of subgiants and dwarfs. It was also shown that our spectroscopic temperatures for the subgiants would be ~ 50 K cooler if we considered the photometric temperatures as the “correct” scale. This would result in underestimated Fe I abundances by 0.05 dex at most. Therefore, if possible systematic effects do exist in our metallicities (which does not seem to be the case), they would not change the main point of the above discussion: the average metallicities of dwarfs and subgiants are equal within the expected uncertainties.

4.1.3. Departures from LTE in Fe I and Fe II in Dwarfs, Subgiants, and Giants

Given the comparisons in the metallicity distributions (primarily from Fe I but also from Fe II lines) between the dwarf, subgiant, and giant samples discussed here, it is important to assess non-LTE Fe I and Fe II line-formation as a function of T_{eff} , surface gravity, and stellar metallicity. Within the homogeneous LTE analysis conducted in this study, planet-hosting dwarf and subgiant stars display the same $[\text{Fe}/\text{H}]$ distributions, while there is an overall difference of ~ 0.2 dex in the Fe-abundance distributions of dwarfs and subgiants with planets when compared to giants with planets. Could this difference be due simply to different non-LTE effects between dwarfs/subgiants and giants?

Non-LTE Calculations

Non-LTE calculations for iron contain uncertainties due to such quantities as electronic collisional cross-sections, in particular for dipole-forbidden transitions; photoionization cross-sections, in particular those from the excited states; a treatment of upper states (particularly those for which no laboratory-measured energies are available); recombination to the upper levels; a treatment of autoionizing levels and related photoionization resonances; and, most importantly, uncertainties due to treatment of collisions with neutral hydrogen atoms, which are poorly known (I. Hubeny 2010, private communication). Within these uncertainties, however, results from non-LTE calculations in cool stars (e.g., Mashonkina et al. 2010a; Gehren et al. 2001a, 2001b) generally find that departures from LTE become larger in very metal-poor stars, evolved stars, and stars with effective temperatures $T_{\text{eff}} > 6000$ K. In the temperature and gravity regimes considered here, non-LTE departures are much less important for Fe II lines, which are generally found to be closer to LTE.

Certain studies of non-LTE in Fe I and Fe II find rather small departures from LTE, even in rather metal-poor stars, such as globular cluster stars. For example, Korn et al. (2003) analyze MS turnoff stars, subgiants, and giants in the globular cluster NGC 6397 (with $[\text{Fe}/\text{H}] = -2.35$) and find total corrections to LTE of Fe I of only 0.03–0.05 dex, with no differential non-LTE effects between the MS turnoff and giant stars. A more recent analysis of this cluster by Lind et al. (2009) notes that such small corrections found by Korn et al. (2003) were probably due to their adoption of rather high efficiencies of collisions between iron atoms and neutral hydrogen atoms, as parameterized by the H I collision enhancement factor of $S_{\text{H}} = 3$.

Given that one of the major uncertainties in non-LTE calculations, as discussed above, is the efficiency of collisions of Fe I with neutral hydrogen, Mashonkina et al. (2010a) present

results for H I collision enhancement factors, S_H , varying between 0 (which corresponds to the strongest non-LTE case) and 2 (corresponding to a situation closer to LTE), as well as LTE. Figure 1 in their study illustrates differences between non-LTE Fe I and Fe II abundances for four different stars: Procyon ($T_{\text{eff}} = 6510$ K, $\log g = 3.96$, $[\text{Fe}/\text{H}] = -0.10$), β Vir ($T_{\text{eff}} = 6060$ K, $\log g = 4.11$, $[\text{Fe}/\text{H}] = +0.04$), τ Cet ($T_{\text{eff}} = 5377$ K, $\log g = 4.53$, $[\text{Fe}/\text{H}] = -0.43$), and HD 84937 ($T_{\text{eff}} = 6350$ K, $\log g = 4.00$, $[\text{Fe}/\text{H}] = -1.94$). It is clear from this figure that non-LTE Fe I abundances of the most metal-poor stars in the sample can be affected by as much as 0.15 dex when $S_H = 0$, however this is only for the most metal-poor star in the sample, HD 84937; the effect of non-LTE on Fe I decreases significantly for increasing metallicities due to increasing electron densities. In addition, values of S_H as low as 0.1 lead to very small non-LTE corrections for Fe I for all stars. Although uncertain, the value $S_H = 0.1$ is favored (Mashonkina et al. 2010c) and this would suggest that differences in the iron abundances between the samples of near-solar metallicity dwarfs, subgiants, and giants caused by non-LTE corrections would be less than 0.1 dex.

The calculations presented in Mashonkina et al. (2010a) predict that non-LTE corrections for Fe I increase strongly with decreasing metallicity and, therefore, should be minimal at solar metallicities. In addition, the corrections become increasingly important for effective temperatures greater than $T_{\text{eff}} = 6000$ K, as well as $\log g \leq 2.00$. The sample analyzed here is dominated by stars with $\log g \geq 2.00$, $T_{\text{eff}} = 4500$ – 6000 K, and near-solar metallicities, where the predicted effects on Fe I are less than 0.1 dex. More recent results presented in Mashonkina et al. (2010b) increase the number of stars to five, and indicate that LTE can be considered “as good as non-LTE” for $S_H > 0.1$ and metallicities between solar and -0.5 dex, based on the analysis of stars such as Procyon and τ Cet. With values of $S_H \sim 0.1$, combined with the points described above, LTE abundances from Fe I and Fe II are expected to be very close to those derived from non-LTE (within hundredths of a dex) for the samples of stars with planets studied here.

Observations of Fe in Dwarfs and Giants in Clusters

The theoretically predicted small non-LTE effects on Fe I described above for near-solar metallicity stars are born out by observations of real stars in clusters which contain uniform Fe abundances. One recent result relevant to this discussion is the abundance analysis of giants, subgiants, and MS stars from a number of open clusters by Santos et al. (2009), as well as the results from the analysis of MS turnoff stars, subgiants, and giants in the globular cluster M71 (one of the more metal-rich globular clusters) by Ramírez et al. (2001). A short summary of these studies would note that no significant abundance differences (i.e., $\Delta[\text{Fe}/\text{H}] \geq 0.05$ dex) were found in LTE analyses of Fe I lines between stars with $T_{\text{eff}} \sim 6000$ – 6100 K and $\log g \sim 4.2$ – 4.6 when compared to those with $T_{\text{eff}} \sim 4500$ – 4600 K and $\log g \sim 1.7$ – 2.5 in any of the studied clusters. Iron abundances from these studies are illustrated in Figure 6 for the globular cluster M71 (Ramírez et al. 2001) and the open clusters NGC 2682 and IC 4651 (Santos et al. 2009); these particular clusters are shown as the numbers of stars studied in each cluster were the largest, and the clusters span a range in $[\text{Fe}/\text{H}]$ overlapping that of the sample stars included here. The top panel shows Fe abundances (as $[\text{Fe}/\text{H}]$) plotted versus T_{eff} and the bottom panel is $[\text{Fe}/\text{H}]$ versus $\log g$. The points are average values for stars found along the major phases of stellar evolution (MS, turnoff, subgiant, and giant branches), with the

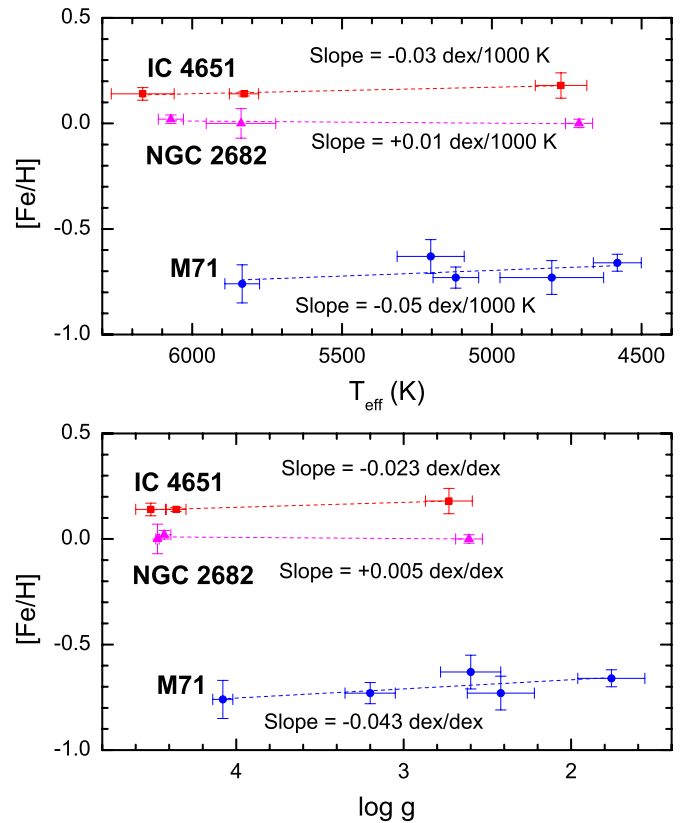


Figure 6. Iron abundances vs. effective temperatures (top panel) and surface gravities (bottom panel) for the globular cluster M71 (Ramírez et al. 2001; blue circles) and the open clusters NGC 2682 and IC 4651 (Santos et al. 2009; respectively, magenta triangles and red squares). The dashed lines show the linear fit to the points for each case. No significant slopes are observed for any of the clusters.

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

standard deviations in $[\text{Fe}/\text{H}]$, T_{eff} , and $\log g$ shown for each sub-sample. Linear least-squares fits were carried out for each cluster and the derived slopes are labeled. For the near-solar metallicity open clusters, in particular, the slopes are very small and not significant indicating a good agreement between the LTE Fe abundances in dwarfs and giants.

Another piece of evidence that the Fe abundances of the stars analyzed here are not affected by significant non-LTE effects is the comparison of stellar surface gravities derived from the enforcement of LTE ionization equilibrium between Fe I and Fe II, with surface gravities derived from fitting stellar models to luminosities obtained from *Hipparcos* parallaxes (so-called *Hipparcos* gravities), as illustrated in Figure 3. If Fe I and/or Fe II suffer from significant departures from LTE, gravities may be adversely affected. The mean difference in $\log g$ between these methods for subgiants and giants is $\log g_{\text{Hipp}} - \log g_{\text{Spec}} = -0.04 \pm 0.12$ dex. The standard deviation in this difference compares well with the expected uncertainty in defining $\log g$ by any method, while the small offset of 0.04 dex indicates excellent agreement between the two surface gravity methods. This small difference indicates that there are not significant departures from LTE populations in Fe I and Fe II in the line-forming regions of near-solar metallicity dwarfs, subgiants, and giants in the T_{eff} and $\log g$ regimes analyzed here.

As the analysis of all stars in the present study was done in a strictly homogeneous manner, coupled to the predictions that non-LTE corrections to Fe I in near-solar metallicity dwarfs

and giants within the range of stellar parameters studied here will be small (much less than 0.1 dex), and the observations of rather uniform LTE iron abundances derived in cluster dwarfs and giants, it is unlikely that non-LTE departures can explain the differences observed here in the iron abundances of dwarfs/subgiants with planets, when compared to giants with planets (~ 0.2 dex).

4.1.4. Dwarfs, Subgiants, Giants, Dilution, and Other Possibilities

The fact that the metallicity distribution of giant stars with planets in our sample is generally more metal poor than the metallicity distribution found for the dwarfs cannot be explained in terms of Galactic chemical evolution, as these results are opposite from what would be expected from chemical evolution: the giant sample stars being younger (on average) than the sample dwarfs would be more metal rich if one considers the effects of an age–metallicity relation. Haywood (2009) propose, on the other hand, that the difference in the metallicity distributions of dwarfs and giants with planets is not related to the formation process of giants planets themselves, but results from a galactic effect instead. His conclusions are based on ages and metallicities of sample giants and dwarfs analyzed by Takeda (2007) and Takeda et al. (2008). As radial mixing is a secular process, the sample of giants would be less contaminated by old, metal-rich wanderers of the inner disk. This scenario would only hold, however, if stars from the inner disk have a higher percentage of giant planets than stars born at the solar radius and assumes a metallicity gradient for the Galactic disk.

A relevant question concerning metallicity distributions of planet-hosting stars in different evolutionary stages connects the possibility of late accretion of metal-rich material onto the star to the dilution of this abundance signature as the star develops a deeper convective envelope. The expectation in such a scenario would be that the metal-rich signature which is due to accretion would vanish as stars become giants; their convective zones become larger and the metal-rich material becomes diluted. If the high metallicity observed for the MS stars hosting giant planets is indeed restricted to the outer envelope, it is expected that subgiants will have a systematically lower metallicity than the dwarfs.

Taken at face value, the metallicity distributions of planet-hosting dwarfs, subgiants, and giants obtained in this study are not in line with the dilution picture as there is not a consistent decrease in the average metallicities for planet-hosting stars going from dwarfs (+0.11 dex) to subgiants (+0.12 dex), to giants (-0.06 dex), in particular between the dwarfs and subgiants. In addition, the absence of a trend in the plot of effective temperature versus stellar metallicity for sample subgiants (shown in Figure 7) indicates the absence of dilution on the subgiant branch. A trend in the run of metallicity with effective temperature would be expected if the stars experienced increased dilution as they evolve redward on the subgiant branch, but this gradient is flat. The giants in our sample which are at the base of the RGB (with $M_{\text{bol}} \simeq 2.82$; see Figure 2) are also shown in Figure 7 as it is at this stage that the convective zone deepens significantly. Note that a similar range in metallicity (roughly between $[\text{Fe}/\text{H}] = -0.3$ to $+0.3$ dex) is encompassed by the subgiants and giants in the figure, which indicates no significant differences between the metallicities of subgiants and giants at the base of the RGB. This result is in agreement with the findings of Fischer & Valenti (2005) who also do not find a metallicity gradient as a function of T_{eff} along the subgiant branch and conclude that subgiants do

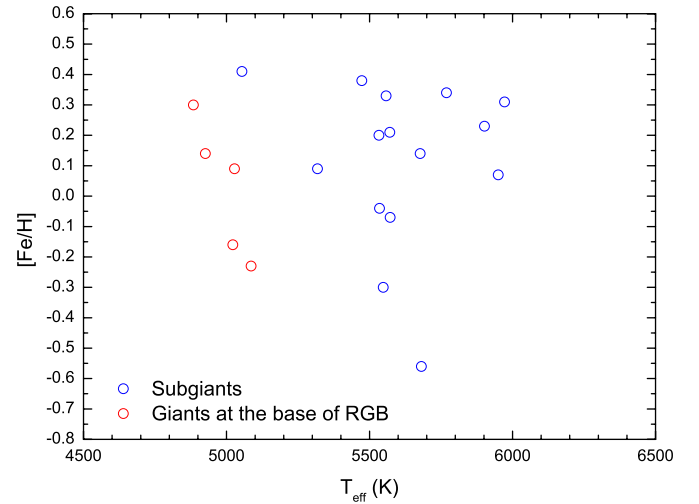


Figure 7. Metallicities vs. effective temperatures for the studied sample of subgiant stars hosting planets (blue open circles). The absence of a trend in this figure indicates that the stars are not experiencing increasing dilution of metal-rich material in their convective zones. Sample giants (red open circles) which are at the base of the RGB ($M_{\text{bol}} \simeq 2.82$) are also shown for comparison. (A color version of this figure is available in the online journal.)

not exhibit any evidence for dilution (see also Johnson et al. 2010a).

Without evidence for dilution along the subgiant branch, the observations point to a scenario to explain the more metal-poor distribution observed for giant stars in comparison with dwarfs which is related to the fact that the higher masses of the giant stars compensate for the lower metallicities by allowing, or favoring, the formation of planets because higher mass stars have on average disks with larger masses. A number of studies (e.g., Natta et al. 2000) find that disk mass increases with stellar mass. As disk mass increases, the surface density (σ) within typical protoplanetary disks also increases and larger values of σ favor the formation of giant planets in the core accretion model of planetary formation (Ida & Lin 2004; Laughlin et al. 2004; see also Johnson et al. 2010a). The precipitation of a substantial planetary core which begins to accrete gas requires a threshold density of solid material (which consists of the heavier elements, or metals).

The observation that the average metallicity of planet-hosting stars is related to the average mass within a stellar sample, with giants representing the more massive but lower metallicity population, is taken as an observational signature of core-accretion as the main mechanism for planetary formation, at least for planets which form relatively close to their parent stars. The disk instability mechanism (see the review by Boss 2010) may still be important for the massive planets which form at large distances from their parent stars. Examples of such systems may be the recently imaged planets found around HR 8799 (Marois et al. 2008) and Fomalhaut (Kalas et al. 2008). The nature of planetary system architectures is quite likely a function of both stellar mass and metallicity.

5. CONCLUSIONS

It is now well established that stars hosting giant planets have on average higher metallicities than stars which do not host closely orbiting giant planets (see, e.g., Gonzalez 2006; Udry & Santos 2007; Valenti 2010 for reviews). So far, however, most of the studies have concentrated on host stars which are on the MS. Such a finding was recently corroborated from

metallicities obtained in the homogeneous analysis of a large sample of MS planet hosts and a control sample of stars without closely orbiting giant planets, which was presented in Paper I. The present study extends the MS sample in Paper I by adding planet-hosting stars which are evolved from the MS.

We have determined stellar parameters and metallicities for a sample of 15 subgiants and 16 giants with planets discovered via RV surveys and 14 comparison subgiants which have been found to exhibit nearly constant RVs and are not likely to host large, closely orbiting planets. The stellar parameters and iron abundances were derived from a classical spectroscopic analysis (similar to Paper I).

Our results are summarized as follows.

1. One strong point of the present study is the strictly homogeneous abundance analyses performed for the samples of dwarfs (Paper I), subgiants, and giants. An additional important aspect is the sample of disk subgiant stars which are known to be RV stable (Fischer & Valenti 2005) and can be used as a comparison sample for the subgiant planet-hosting stars.
2. The subgiant sample in this study is found to be a slightly older population which has evolved mostly from the same underlying population as the dwarfs analyzed in Paper I; the sample dwarfs and subgiants have significant overlap in their mass ranges. The sample giants, however, are evolved from stars which are more massive and are, on average, the youngest of all studied targets.
3. The metallicity distribution obtained for our sample of 16 planet-hosting giant stars displays an average that is more metal poor by 0.17 dex than the metallicity distribution obtained in Paper I for the sample of planet-hosting dwarfs ($N = 117$). When literature iron abundance results for all other presently known planet-hosting giant stars are included, in order to improve the giant star statistics to a total of 37 stars, the offset in the average metallicities between dwarf and planet-hosting giant stars is confirmed and becomes marginally larger (0.23 dex).
4. The average metallicity of the planet-hosting subgiant sample is metal rich relative to the Sun, $\langle[\text{Fe}/\text{H}]\rangle = +0.12$ dex. The latter distribution is similar to that obtained for the planet-hosting dwarf sample, and on average more metal rich than that of subgiants without planets by 0.21 dex. This abundance difference between the subgiants with and without planets is in general agreement, within the uncertainties, with the abundance shift that is found for dwarfs with and without planets.
5. The absence of a trend in the derived iron abundances with effective temperature for the sample subgiant stars shows no evidence for dilution on the subgiant branch. This flat gradient plus the fact that there is not a significant difference between the metallicity distributions of planet-hosting subgiant stars in comparison to planet-hosting dwarf stars, as would be expected from the more extended convective envelopes of subgiants in comparison with dwarfs, weakens the possibility of dilution as a viable explanation for the lower metallicity found for the giant stars.
6. In the absence of substantial evidence for the dilution of accreted metal-rich material, the results in this study favor a scenario to explain the more metal-poor distribution observed for giant stars in comparison with that of dwarfs which is related to the fact that the higher masses of the giant stars compensate for the lower metallicities, as higher mass

stars have on average more massive disks with more metals available for planet formation through core accretion.

We thank Leo Girardi for helping with the computation of the evolutionary parameters. K.C. thanks Andreas Korn and Ivan Hubeny for discussions concerning non-LTE effects, and Joan Najita and Luca Pasquini for fruitful discussions. L.G. thanks Oliver Schütz for his valuable help in using the FEROS DRS package and Cláudio Bastos for conducting the observations for target star HD 114613. L.G. acknowledges financial support by CNPq. Research presented here was supported in part by the NASA grant NNNH08AJ581.

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