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Spectroscopic [Fe/H] for 98 extra-solar planet-host stars*

Exploring the probability of planet formation

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Abstract. We present stellar parameters and metallicities, obtained from a detailed spectroscopic analysis, for a large sample of 98 stars known to be orbited by planetary mass companions (almost all known targets), as well as for a volume-limited sample of 41 stars not known to host any planet. For most of the stars the stellar parameters are revised versions of the ones presented in our previous work. However, we also present parameters for 18 stars with planets not previously published, and a compilation of stellar parameters for the remaining 4 planet-hosts for which we could not obtain a spectrum. A comparison of our stellar parameters with values of $T_{\rm eff}$, $\log g$, and [Fe/H] available in the literature shows a remarkable agreement. In particular, our spectroscopic $\log g$ values are now very close to trigonometric $\log g$ estimates based on Hipparcos parallaxes. The derived [Fe/H] values are then used to confirm the previously known result that planets are more prevalent around metal-rich stars. Furthermore, we confirm that the frequency of planets is a strongly rising function of the stellar metallicity, at least for stars with [Fe/H] > 0. While only about 3% of the solar metallicity stars in the CORALIE planet search sample were found to be orbited by a planet, this number increases to more than 25% for stars with [Fe/H] above +0.3. Curiously, our results also suggest that these percentages might remain relatively constant for values of [Fe/H] lower than about solar, increasing then linearly with the mass fraction of heavy elements. These results are discussed in the context of the theories of planetary formation.

Key words. stars: abundances – stars: fundamental parameters – stars: planetary systems – stars: planetary systems: formation – stars: chemically peculiar

1. Introduction

The discovery of now more than 115 giant planets orbiting solar-type stars[1] has lead to a number of different studies on the formation and evolution of the newly found planetary systems (for a recent review see e.g. Mayor 2003 or Santos et al. 2003b). With the numbers increasing, current analyses are giving us the first statistically significant results about the properties of the new systems (e.g. Jorissen et al. 2001; Zucker & Mazeh 2002; Udry et al. 2003; Santos et al. 2003a; Eggenberger et al. 2003). Amongst these, some deal with the planet-host stars themselves: they were found to be significantly metal-rich with respect to the average field dwarfs (e.g. Gonzalez 1997, 1998; Fuhrmann et al. 1998; Santos et al. 2000, 2001, 2003a; Gonzalez et al. 2001; Reid 2002; Laws et al. 2003).

Current studies seem to favor that this "excess" metallicity has a primordial origin, i.e., that the high metal content of the stars was common to the cloud of gas and dust that gave origin to the star-planet system (Pinsonneault et al. 2001; Santos et al. 2001, 2003a). Furthermore, it has been shown that the frequency of planetary companions is a strong function of the metal content of the star (Santos et al. 2001, 2003a; Reid 2002): it is much easier to find planets around metal-rich objects. Overall, the results suggest that the formation of giant planets (or at least of the kind we find now) is very dependent on the grain content of the disk, a result that has important consequences for theories of planetary formation (Pollack et al. 1996; Boss 2002; Rice & Armitage 2003).

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* Based on observations collected at the La Silla Observatory, ESO (Chile), with the CORALIE spectrograph at the 1.2-m Euler Swiss telescope and the FEROS spectrograph at the 1.52-m and 2.2-m ESO telescopes, with the VLT/UT2 Kueyen telescope (Paranal Observatory, ESO, Chile) using the UVES spectrograph (Observing run 67.C-0206, in service mode), with the TNG and William Herschel Telescopes, both operated at the island of La Palma, and with the ELODIE spectrograph at the 1.93-m telescope at the Observatoire de Haute Provence.

[1] See e.g. table at `http://obswww.unige.ch/Exoplanets` for a continuously updated version.

During the last few years we have gathered spectra for planet host stars, as well as of a sample of objects not known to harbor any planetary companion. The main results of our uniform study, concerning the metallicity of planet host stars, have been presented in Santos et al. (2000, 2001, 2003a) (hereafter Papers I, II, and III, respectively).

Most groups working on exoplanets are now convinced that planet host stars are really more metal-rich than average field dwarfs. This result is clearly independent of the kind of analysis done to obtain the stellar metallicity (e.g. Giménez 2000; Gonzalez et al. 2001; Santos et al. 2001; Murray & Chaboyer 2002; Martell & Laughlin 2002; Heiter & Luck 2003), and in Paper III we showed that this result is not due to any observational bias. However, some authors have questioned the quality of the spectroscopic analyses we (and others) have been publishing. In particular, the relatively high surface gravities derived in our preceding papers led to some criticism regarding this matter.

In order to address this problem, in this paper we present a revised spectroscopic analysis for all the stars presented in Papers II and III. The new derived surface gravities are now compatible with the ones obtained by other authors, and with trigonometric gravities derived using Hipparcos parallaxes (ESA 1997). Other stellar parameters ($T_{\rm eff}$ and [Fe/H]) are also similar to the ones presented elsewhere in the literature, and not particularly different from the ones derived in Papers II and III.

Furthermore, we have derived stellar parameters for 18 planet host stars not analyzed before, increasing to 98 the number of these objects for which we have precise spectral information. The new results unambiguously confirm the previously presented trends: stars with planetary companions are more metal-rich than average field dwarfs.

2. The data

Most of the spectra for the planet-host stars analyzed in this paper were studied in Papers I, II, and III. We refer the reader to these for a description of the data.

During the last year, however, we have obtained spectra for 18 more planet host stars. Most of the spectra were gathered using the FEROS spectrograph (2.2-m ESO/MPI telescope, La Silla, Chile), on the night of the 12–13 March 2003 (for HD 47536, HD 65216, HD 72659, HD 73256, HD 73526, HD 76700, HD 111232, and HD 142415) and with the SARG spectrograph at the TNG telescope (La Palma, Spain) on the nights of the 9–10 October 2003 (for HD 3651, HD 40979, HD 68988, HD 216770, HD 219542B, and HD 222404). In these runs we have also gathered spectra for HD 30177, HD 162020 (FEROS), and HD178911B (SARG), already previously analyzed. The FEROS spectra have S/N ratios above 300 for all targets at a resolution of about 50 000, and were reduced using the FEROS pipeline software. The SARG spectra have a resolution of about 57 000, and were reduced using the tasks within the IRAF `echelle` package[2]. Finally, a spectrum of HD 70642 with a $S/N \sim 150$ was obtained using the CORALIE spectrograph ($R = 50\,000$), at the 1.2-m Euler Swiss telescope (La Silla, Chile), on the night of the 21–22 October 2003.

Equivalent widths (EW) were measured using a Gaussian fitting procedure within the IRAF `splot` task. For HD 178911 B, we also used the EW measured by Zucker et al. (2001) from a Keck/HIRES spectrum (Zucker & Latham, private communication). Given that only 16 Fe I and 2 Fe II lines were measured from this spectrum, the parameters derived are only listed as a test of consistency, but are not used in rest of the paper. Other previously obtained, but not used, spectra (see Paper III for the instrument description) were also analyzed for HD 89744 and HD 19994 (WHT/UES), HD 120136 (VLT/UVES), HD 49674 (TNG/SARG).

Besides the planet host stars, we also re-analyzed here our comparison sample of stars not known to harbor any planetary companion. This volume-limited sample, that represents a sub-sample of the CORALIE planet search program stars (Udry et al. 2000), is described in Paper II. Since 2001, however, 2 of the stars in the original list have been found to harbor planetary-mass companions: HD 39091 (Jones et al. 2002) and HD 10647 (Mayor et al. 2003). These are thus considered now as planet hosts, adding to HD1237, HD 13445, HD 17051, HD 22049, HD 217107, also belonging to our original volume limited sample, but known as planet hosts by the time Paper II was published. These stars should, however, be taken into account for completeness.

3. Spectroscopic analysis and stellar parameters

For the past three years we have been deriving stellar parameters for planet-host stars and for a comparison sample of stars with no detected planetary companions (Papers I, II and III). However, the stellar parameters presented in our previous studies were not completely satisfactory. In particular, the derived surface gravities were systematically higher than the ones obtained by other authors (see e.g. Gonzalez et al. 2001) by ~0.15 dex. While this fact was clearly not producing an important shift in the final metallicities (see e.g. Santos et al. 2003a; Laws et al. 2003), this lead some authors to suggest that the metallicity excess observed was not real (Wuchterl, private communication).

To solve this problem we have carried out a new spectroscopic analysis of all the program stars. The stellar parameters were derived using the same technique as in the previous papers, based on about 39 Fe I and 12 Fe II lines (see Table 1), and the spectroscopic analysis was done in LTE using the 2002 version of the code MOOG (Sneden 1973)[3]. However, 2 main changes have been done. Firstly, we have adopted new $\log gf$ values for the iron lines. These were computed from an inverted solar analysis using solar EW measured from the Kurucz Solar Atlas (Kurucz et al. 1984), and

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[2] IRAF is distributed by National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation, USA.

[3] The code MOOG (2002) can be downloaded at `http://verdi.as.utexas.edu/moog.html`

Table 1. Atomic parameters and measured solar equivalent widths for the Fe I and Fe II lines used.

λ (Å)	χ_l	$\log gf$	$EW_\odot$ (mÅ)
Fe I			
5044.22	2.85	−2.04	73.4
5247.06	0.09	−4.93	66.8
5322.05	2.28	−2.90	60.4
5806.73	4.61	−0.89	53.7
5852.22	4.55	−1.19	40.6
5855.08	4.61	−1.53	22.4
5856.09	4.29	−1.56	33.8
6027.06	4.08	−1.18	64.3
6056.01	4.73	−0.50	72.4
6079.01	4.65	−1.01	45.7
6089.57	5.02	−0.88	35.0
6151.62	2.18	−3.30	49.8
6157.73	4.07	−1.24	61.9
6159.38	4.61	−1.86	12.4
6165.36	4.14	−1.50	44.6
6180.21	2.73	−2.64	55.8
6188.00	3.94	−1.63	47.7
6200.32	2.61	−2.40	73.3
6226.74	3.88	−2.07	29.3
6229.24	2.84	−2.89	37.9
6240.65	2.22	−3.29	48.3
6265.14	2.18	−2.56	86.0
6270.23	2.86	−2.58	52.3
6380.75	4.19	−1.32	52.2
6392.54	2.28	−3.93	18.1
6498.94	0.96	−4.63	45.9
6591.32	4.59	−1.98	10.6
6608.03	2.28	−3.96	17.7
6627.55	4.55	−1.48	28.0
6646.94	2.61	−3.94	9.9
6653.86	4.15	−2.41	10.5
6703.57	2.76	−3.02	36.9
6710.32	1.48	−4.82	16.0
6725.36	4.10	−2.20	17.2
6726.67	4.61	−1.05	46.9
6733.16	4.64	−1.43	26.8
6750.16	2.42	−2.61	74.1
6752.71	4.64	−1.23	35.9
6786.86	4.19	−1.90	25.2
Fe II			
5234.63	3.22	−2.23	83.7
5991.38	3.15	−3.53	31.5
6084.11	3.20	−3.78	20.8
6149.25	3.89	−2.72	36.2
6247.56	3.89	−2.35	52.2
6369.46	2.89	−4.13	19.2
6416.93	3.89	−2.64	40.1
6432.69	2.89	−3.56	41.5
6446.40	6.22	−1.91	4.2
7479.70	3.89	−3.59	10.0
7515.84	3.90	−3.43	13.4
7711.73	3.90	−2.55	46.0

a Kurucz grid model for the Sun (Kurucz 1993) having ($T_{\rm eff}$, $\log g$, $\xi_{\rm t}$, $\log \epsilon_{\rm Fe}$) = (5777 K, 4.44 dex, 1.00 km s^{-1}, 7.47 dex). This differs from our previous analysis where we always used $\log gf$ values taken from Gonzalez et al. (2001 and references therein). Secondly, we have now used a van der Walls damping based on the Unsold approximation, but multiplied by a factor as suggested by the Blackwell group (option 2 in the damping parameter inside MOOG).

We also note that our previous analysis was done using an older version of MOOG. A comparison showed that for some cases there were slight differences in the derived stellar metallicities, but never exceeding 0.01 dex.

As a test, we computed the Solar parameters and iron abundances based on iron *EW* measured using a Solar spectrum taken with the HARPS spectrograph (courtesy of the HARPS team, Mayor et al.). The resulting parameters were $T_{\rm eff}$ = 5779 ± 23, $\log g$ = 4.48 ± 0.07, $\xi_{\rm t}$ = 1.04 ± 0.04, and [Fe/H] = 0.00 ± 0.03, very close (and within the errors) to the "expected" solution (there are almost no differences in average between the solar *EW* derived from the Kurucz Atlas compared to the ones derived from the HARPS spectrum).

The atmospheric parameters for our program stars were obtained from the Fe I and Fe II lines by iterating until the correlation coefficients between $\log \epsilon$(Fe I) and χ_l, and between $\log \epsilon$(Fe I) and $\log (W_\lambda/\lambda)$ were zero, and the mean abundance given by Fe I and Fe II lines were the same. To simplify this analysis, we built a Fortran code that uses a Downhill Simplex Method (Press et al. 1992) to find the best solution in the (stellar) parameter space (which happens in most of the cases after a few minutes). The results are thus obtained in a fast and automatic way, once the *EW* are measured.

The final stellar parameters and masses are presented in Tables 2 through 5, for planet-host stars and for our comparison sample objects[4]. The errors were derived as described in Paper I, and are of the order of 50 K in $T_{\rm eff}$, 0.12 dex in $\log g$, 0.08 km s^{-1} in the microturbulence, and 0.05 dex in the metallicity. Stellar masses were computed by interpolating the theoretical isochrones of Schaller et al. (1992), and Schaerer et al. (1992, 1993), using M_V computed using Hipparcos parallaxes

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[4] These tables are also available in electronic form at CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/415/1153`

Table 2. Stars with planets and derived stellar parameters (HD number between 1 and 60 000). See text for more details.

HD number	$T_{\rm eff}$ [K]	$\log g_{\rm spec}$ [cm s^{-2}]	$\xi_{\rm t}$ [km s^{-1}]	[Fe/H]	N(Fe I, Fe II)	σ(Fe I, Fe II)	Instr.[a]	Mass [$M_\odot$]	$\log g_{\rm hipp}$ [cm s^{-2}]
HD 142	6302 ± 56	4.34 ± 0.13	1.86 ± 0.17	0.14 ± 0.07	28, 8	0.05, 0.05	[2]	1.28	4.27
HD 1237	5536 ± 50	4.56 ± 0.12	1.33 ± 0.06	0.12 ± 0.06	37, 7	0.05, 0.06	[1]	0.99	4.56
HD 2039	5976 ± 51	4.45 ± 0.10	1.26 ± 0.07	0.32 ± 0.06	34, 6	0.05, 0.04	[1]	1.18	4.35
HD 3651	5173 ± 35	4.37 ± 0.12	0.74 ± 0.05	0.12 ± 0.04	31, 5	0.04, 0.05	[4]	0.76	4.41
HD 4203	5636 ± 40	4.23 ± 0.14	1.12 ± 0.05	0.40 ± 0.05	37, 7	0.05, 0.07	[2]	1.06	4.19
HD 4208	5626 ± 32	4.49 ± 0.10	0.95 ± 0.06	−0.24 ± 0.04	37, 7	0.04, 0.05	[2]	0.86	4.48
HD 6434	5835 ± 59	4.60 ± 0.12	1.53 ± 0.27	−0.52 ± 0.08	30, 4	0.06, 0.06	[2]	0.82	4.33
HD 8574	6151 ± 57	4.51 ± 0.10	1.45 ± 0.15	0.06 ± 0.07	30, 7	0.06, 0.04	[4]	1.18	4.28
HD 9826	6212 ± 64	4.26 ± 0.13	1.69 ± 0.16	0.13 ± 0.08	27, 6	0.06, 0.05	[4]	1.30	4.16
HD 10647	6143 ± 31	4.48 ± 0.08	1.40 ± 0.08	−0.03 ± 0.04	34, 6	0.03, 0.03	[1]	1.14	4.43
HD 10697	5641 ± 28	4.05 ± 0.05	1.13 ± 0.03	0.14 ± 0.04	33, 7	0.03, 0.03	[4]	1.22	4.03
HD 12661	5702 ± 36	4.33 ± 0.08	1.05 ± 0.04	0.36 ± 0.05	34, 8	0.04, 0.03	[3]	1.05	4.34
HD 13445	5119 ± 43	4.48 ± 0.14	0.63 ± 0.07	−0.25 ± 0.05	38, 6	0.05, 0.07	[1]	0.67	4.44
HD 13445	5207 ± 30	4.56 ± 0.11	0.82 ± 0.05	−0.23 ± 0.04	38, 5	0.03, 0.05	[2]	0.74	4.52
HD 13445	5163	4.52	0.72	−0.24			avg.	0.70	4.48
HD 16141	5801 ± 30	4.22 ± 0.12	1.34 ± 0.04	0.15 ± 0.04	37, 7	0.03, 0.04	[2]	1.05	4.17
HD 17051	6252 ± 53	4.61 ± 0.16	1.18 ± 0.10	0.26 ± 0.06	34, 6	0.05, 0.07	[2]	1.32	4.49
HD 19994	6217 ± 67	4.29 ± 0.08	1.62 ± 0.12	0.25 ± 0.08	35, 5	0.06, 0.03	[1]	1.37	4.14
HD 19994	6290 ± 58	4.31 ± 0.13	1.63 ± 0.12	0.32 ± 0.07	33, 6	0.06, 0.05	[2]	1.40	4.17
HD 19994	6121 ± 33	4.06 ± 0.05	1.55 ± 0.06	0.19 ± 0.05	37, 5	0.04, 0.03	[5]	1.34	4.09
HD 19994	6132 ± 67	4.11 ± 0.23	1.37 ± 0.12	0.21 ± 0.08	35, 6	0.06, 0.09	[3]	1.36	4.10
HD 19994	6190	4.19	1.54	0.24			avg.	1.37	4.12
HD 20367	6138 ± 79	4.53 ± 0.22	1.22 ± 0.16	0.17 ± 0.10	31, 6	0.08, 0.09	[6]	1.21	4.42
HD 22049	5073 ± 42	4.43 ± 0.08	1.05 ± 0.06	−0.13 ± 0.04	37, 6	0.05, 0.04	[1]	0.73	4.55
HD 23079	5959 ± 46	4.35 ± 0.12	1.20 ± 0.10	−0.11 ± 0.06	35, 6	0.05, 0.05	[2]	1.01	4.36
HD 23596	6108 ± 36	4.25 ± 0.10	1.30 ± 0.05	0.31 ± 0.05	36, 6	0.04, 0.04	[3]	1.30	4.22
HD 27442	4825 ± 107	3.55 ± 0.32	1.18 ± 0.12	0.39 ± 0.13	36, 6	0.11, 0.13	[2]	–	–
HD 28185	5656 ± 44	4.45 ± 0.08	1.01 ± 0.06	0.22 ± 0.05	38, 6	0.05, 0.03	[1]	0.98	4.39
HD 30177	5591 ± 50	4.35 ± 0.12	1.03 ± 0.06	0.39 ± 0.06	37, 4	0.06, 0.05	[1]	1.01	4.34
HD 30177	5584 ± 65	4.23 ± 0.13	1.14 ± 0.07	0.38 ± 0.09	38, 7	0.07, 0.05	[2]	1.01	4.34
HD 30177	5588	4.29	1.08	0.39			avg.	1.01	4.34
HD 33636[b]	6046 ± 49	4.71 ± 0.09	1.79 ± 0.19	−0.08 ± 0.06	37, 6	0.05, 0.04	[2]	1.16	4.56
HD 37124	5546 ± 30	4.50 ± 0.03	0.80 ± 0.07	−0.38 ± 0.04	36, 7	0.04, 0.02	[3]	0.75	4.33
HD 38529	5674 ± 40	3.94 ± 0.12	1.38 ± 0.05	0.40 ± 0.06	34, 7	0.05, 0.06	[2]	1.60	3.81
HD 39091[b]	5991 ± 27	4.42 ± 0.10	1.24 ± 0.04	0.10 ± 0.04	38, 7	0.03, 0.04	[1]	1.10	4.38
HD 40979	6145 ± 42	4.31 ± 0.15	1.29 ± 0.09	0.21 ± 0.05	24, 9	0.04, 0.07	[4]	1.21	4.38
HD 46375	5268 ± 55	4.41 ± 0.16	0.97 ± 0.06	0.20 ± 0.06	37, 4	0.05, 0.07	[3]	0.82	4.34
HD 47536	4554 ± 85	2.48 ± 0.23	1.82 ± 0.08	−0.54 ± 0.12	37, 6	0.11, 0.09	[2]	–	–
HD 49674	5644 ± 54	4.37 ± 0.07	0.89 ± 0.07	0.33 ± 0.06	33, 5	0.06, 0.04	[4]	1.04	4.50
HD 50554	6026 ± 30	4.41 ± 0.13	1.11 ± 0.06	0.01 ± 0.04	37, 6	0.03, 0.05	[3]	1.09	4.40
HD 52265	6076 ± 57	4.20 ± 0.17	1.38 ± 0.09	0.20 ± 0.07	39, 7	0.06, 0.07	[1]	1.19	4.32
HD 52265	6131 ± 47	4.35 ± 0.13	1.33 ± 0.08	0.25 ± 0.06	36, 6	0.05, 0.04	[2]	1.21	4.34
HD 52265	6103	4.28	1.36	0.23			avg.	1.20	4.33

[a] The instruments used to obtain the spectra were: [1] 1.2-m Swiss Telescope/CORALIE; [2] 1.5-m and 2.2-m ESO/FEROS; [3] WHT/UES; [4] TNG/SARG; [5] VLT-UT2/UVES; [6] 1.93-m OHP/ELODIE; [7] Keck/HIRES.

[b] The companions to these stars have minimum masses above 10 $M_{\rm Jup}$, and are thus probably brown-dwarfs.

(ESA 1997), a bolometric correction from Flower (1996), and the $T_{\rm eff}$ obtained from the spectroscopy. We adopt a typical relative error of 0.05 $M_\odot$ for the masses. In some cases, no mass estimates are presented, since these involved large extrapolations of the isochrones. A comparison with other works shows that (on average) there are almost no differences to the masses derived in the study of Laws et al. (2003), although these authors used a different set of theoretical isochrones; a small difference of 0.03 $M_\odot$ is found with respect to the analysis of Allende Prieto & Lambert (1999).

For comparison, we have also computed the surface gravities based on Hipparcos parallaxes (trigonometric gravities). Using the well known relations $g = \frac{GM}{R^2}$, and $L = 4\pi R^2 \sigma T_{\rm eff}^4$, we can obtain:

$$\log \frac{g}{g_\odot} = \log \frac{M}{M_\odot} + 4 \log \frac{T_{\rm eff}}{T_{\rm eff\odot}} + 2 \log \pi + 0.4(V_0 + {\rm BC}) + 0.11 \quad (1)$$

Table 3. Stars with planets and derived stellar parameters (HD number from 60 000 to 160 000). See text for more details.

HD number	$T_{\rm eff}$ [K]	$\log g_{\rm spec}$ [cm s^{-2}]	$\xi_{\rm t}$ [km s^{-1}]	[Fe/H]	N(Fe I, Fe II)	σ(Fe I, Fe II)	Instr.[a]	Mass [$M_\odot$]	$\log g_{\rm hipp}$ [cm s^{-2}]
HD 65216	5666 ± 31	4.53 ± 0.09	1.06 ± 0.05	−0.12 ± 0.04	38, 7	0.03, 0.05	[2]	0.94	4.53
HD 68988	5988 ± 52	4.45 ± 0.15	1.25 ± 0.08	0.36 ± 0.06	28, 8	0.05, 0.06	[4]	1.18	4.41
HD 70642	5693 ± 26	4.41 ± 0.09	1.01 ± 0.04	0.18 ± 0.04	36, 8	0.03, 0.04	[1]	0.99	4.43
HD 72659	5995 ± 45	4.30 ± 0.07	1.42 ± 0.09	0.03 ± 0.06	36, 7	0.05, 0.02	[2]	1.16	4.22
HD 73256	5518 ± 49	4.42 ± 0.12	1.22 ± 0.06	0.26 ± 0.06	37, 5	0.05, 0.05	[2]	0.98	4.51
HD 73526	5699 ± 49	4.27 ± 0.12	1.26 ± 0.06	0.27 ± 0.06	39, 7	0.05, 0.06	[2]	1.05	4.15
HD 74156	6112 ± 39	4.34 ± 0.10	1.38 ± 0.07	0.16 ± 0.05	35, 6	0.04, 0.03	[2]	1.27	4.16
HD 75289	6143 ± 53	4.42 ± 0.13	1.53 ± 0.09	0.28 ± 0.07	39, 5	0.06, 0.04	[1]	1.23	4.35
HD 75732	5279 ± 62	4.37 ± 0.18	0.98 ± 0.07	0.33 ± 0.07	37, 6	0.06, 0.07	[3]	0.87	4.44
HD 76700	5737 ± 34	4.25 ± 0.14	1.18 ± 0.04	0.41 ± 0.05	38, 8	0.04, 0.06	[2]	1.10	4.26
HD 80606	5574 ± 72	4.46 ± 0.20	1.14 ± 0.09	0.32 ± 0.09	38, 5	0.07, 0.08	[3]	1.04	4.55
HD 82943	6005 ± 41	4.45 ± 0.13	1.08 ± 0.05	0.32 ± 0.05	38, 7	0.04, 0.06	[1]	1.19	4.41
HD 82943	6028 ± 19	4.46 ± 0.02	1.18 ± 0.03	0.29 ± 0.02	35, 6	0.02, 0.02	[5]	1.20	4.43
HD 82943	6016	4.46	1.13	0.30			avg.	1.20	4.42
HD 83443	5454 ± 61	4.33 ± 0.17	1.08 ± 0.08	0.35 ± 0.08	38, 7	0.07, 0.08	[1]	0.93	4.37
HD 89744	6234 ± 45	3.98 ± 0.05	1.62 ± 0.08	0.22 ± 0.05	26, 7	0.04, 0.02	[3]	1.53	3.97
HD 92788	5821 ± 41	4.45 ± 0.06	1.16 ± 0.05	0.32 ± 0.05	37, 5	0.04, 0.02	[1]	1.12	4.49
HD 95128	5954 ± 25	4.44 ± 0.10	1.30 ± 0.04	0.06 ± 0.03	30, 7	0.03, 0.04	[4]	1.07	4.33
HD 106252	5899 ± 35	4.34 ± 0.07	1.08 ± 0.06	−0.01 ± 0.05	37, 6	0.04, 0.04	[1]	1.02	4.39
HD 108147	6248 ± 42	4.49 ± 0.16	1.35 ± 0.08	0.20 ± 0.05	32, 7	0.04, 0.06	[1]	1.27	4.41
HD 108874	5596 ± 42	4.37 ± 0.12	0.89 ± 0.05	0.23 ± 0.05	29, 6	0.04, 0.05	[3]	0.97	4.27
HD 111232	5494 ± 26	4.50 ± 0.10	0.84 ± 0.05	−0.36 ± 0.04	36, 6	0.03, 0.05	[2]	0.75	4.40
HD 114386	4804 ± 61	4.36 ± 0.28	0.57 ± 0.12	−0.08 ± 0.06	35, 4	0.06, 0.14	[1]	0.54	4.40
HD 114729	5886 ± 36	4.28 ± 0.13	1.25 ± 0.09	−0.25 ± 0.05	26, 5	0.04, 0.04	[3]	0.97	4.13
HD 114762[b]	5884 ± 34	4.22 ± 0.02	1.31 ± 0.17	−0.70 ± 0.04	34, 5	0.04, 0.02	[5]	0.81	4.17
HD 114783	5098 ± 36	4.45 ± 0.11	0.74 ± 0.05	0.09 ± 0.04	27, 6	0.04, 0.05	[4]	0.77	4.52
HD 117176	5560 ± 34	4.07 ± 0.05	1.18 ± 0.05	−0.06 ± 0.05	33, 6	0.04, 0.02	[4]	0.93	3.87
HD 120136	6339 ± 73	4.19 ± 0.10	1.70 ± 0.16	0.23 ± 0.07	24, 4	0.05, 0.04	[5]	1.33	4.25
HD 121504	6075 ± 40	4.64 ± 0.12	1.31 ± 0.07	0.16 ± 0.05	39, 7	0.04, 0.05	[1]	1.17	4.41
HD 128311	4835 ± 72	4.44 ± 0.21	0.89 ± 0.11	0.03 ± 0.07	26, 5	0.07, 0.09	[3]	0.61	4.43
HD 130322	5392 ± 36	4.48 ± 0.06	0.85 ± 0.05	0.03 ± 0.04	32, 6	0.04, 0.03	[4]	0.96	4.61
HD 134987	5776 ± 29	4.36 ± 0.07	1.09 ± 0.04	0.30 ± 0.04	31, 7	0.03, 0.03	[4]	1.08	4.32
HD 136118[b]	6222 ± 39	4.27 ± 0.15	1.79 ± 0.12	−0.04 ± 0.05	27, 7	0.03, 0.06	[4]	1.29	4.12
HD 137759	4775 ± 113	3.09 ± 0.40	1.78 ± 0.11	0.13 ± 0.14	29, 7	0.12, 0.18	[4]	–	–
HD 141937	5909 ± 39	4.51 ± 0.08	1.13 ± 0.06	0.10 ± 0.05	38, 7	0.04, 0.03	[3]	1.08	4.45
HD 142415	6045 ± 44	4.53 ± 0.08	1.12 ± 0.07	0.21 ± 0.05	38, 7	0.05, 0.04	[2]	1.26	4.57
HD 143761	5853 ± 25	4.41 ± 0.15	1.35 ± 0.07	−0.21 ± 0.04	31, 6	0.03, 0.06	[4]	0.95	4.20
HD 145675	5311 ± 87	4.42 ± 0.18	0.92 ± 0.10	0.43 ± 0.08	29, 5	0.06, 0.05	[4]	0.90	4.41
HD 147513	5883 ± 25	4.51 ± 0.05	1.18 ± 0.04	0.06 ± 0.04	36, 7	0.03, 0.03	[1]	1.11	4.53
HD 150706	5961 ± 27	4.50 ± 0.10	1.11 ± 0.06	−0.01 ± 0.04	27, 5	0.03, 0.05	[3]	1.17	4.59

[a] The instruments used to obtain the spectra were: [1] 1.2-m Swiss Telescope/CORALIE; [2] 1.5-m and 2.2-m ESO/FEROS; [3] WHT/UES; [4] TNG/SARG; [5] VLT-UT2/UVES; [6] 1.93-m OHP/ELODIE; [7] Keck/HIRES.

[b] The companions to these stars have minimum masses above 10 $M_{\rm Jup}$, and are probably Brown-Dwarfs.

where BC is the bolometric correction, V_0 the visual magnitude, and π the parallax. Here we used a solar absolute magnitude $M_v = 4.81$ (Bessell et al. 1998) and, for consistency, we took the bolometric correction derived for a solar temperature star (−0.08) using the calibration of Flower (1996)[5]. This method was already successfully used by other authors, namely Allende Prieto et al. (1999) and Nissen et al. (1997), in obtaining surface gravities for stars with precise parallax estimates. Given the proximity of our targets (typical values of $\sigma(\pi)/\pi$ are lower than 0.05, and always lower than 0.10 except for HD 80606), the derived trigonometric surface gravities are reasonably free from the Lutz-Kelker effect (Lutz & Kelker 1973;

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[5] We can find some differences in the literature regarding these values (see e.g. Bessell et al. 1998; Bergbusch & Vanderberg 1992), which can introduce systematic errors in the resulting trigonometric parallaxes. In particular, there seems to be a large discrepancy regarding the solar BC derived using Kurucz models (see Bessell et al. 1998).

Table 4. Stars with planets and derived stellar parameters (HD number from 160 000 on). See text for more details.

HD number	$T_{\rm eff}$ [K]	$\log g_{\rm spec}$ [cm s^{-2}]	$\xi_{\rm t}$ [km s^{-1}]	[Fe/H]	N(Fe I, Fe II)	σ(Fe I, Fe II)	Instr.[a]	Mass [$M_\odot$]	$\log g_{\rm hipp}$ [cm s^{-2}]
HD 160691	5798 ± 33	4.31 ± 0.08	1.19 ± 0.04	0.32 ± 0.04	36, 7	0.04, 0.03	[1]	1.10	4.25
HD 162020[b]	4835 ± 72	4.39 ± 0.25	0.86 ± 0.12	−0.09 ± 0.07	36, 4	0.07, 0.1	[1]	0.66	4.56
HD 162020[b]	4882 ± 91	4.44 ± 0.35	0.87 ± 0.16	0.01 ± 0.08	35, 4	0.08, 0.18	[2]	0.80	4.67
HD 162020[b]	4858	4.42	0.86	−0.04			avg.	0.73	4.62
HD 168443	5617 ± 35	4.22 ± 0.05	1.21 ± 0.05	0.06 ± 0.05	31, 7	0.04, 0.02	[4]	0.96	4.05
HD 168746	5601 ± 33	4.41 ± 0.12	0.99 ± 0.05	−0.08 ± 0.05	38, 7	0.04, 0.05	[1]	0.88	4.31
HD 169830	6299 ± 41	4.10 ± 0.02	1.42 ± 0.09	0.21 ± 0.05	38, 4	0.04, 0.01	[1]	1.43	4.09
HD 177830	4804 ± 77	3.57 ± 0.17	1.14 ± 0.09	0.33 ± 0.09	31, 4	0.08, 0.04	[4]	–	–
HD 178911B[c]	5588 ± 115	4.46 ± 0.20	0.82 ± 0.14	0.24 ± 0.10	16, 2	0.06, 0.02	[7]	0.97	3.73
HD 178911B	5600 ± 42	4.44 ± 0.08	0.95 ± 0.05	0.27 ± 0.05	30, 6	0.04, 0.04	[4]	0.98	3.74
HD 179949	6260 ± 43	4.43 ± 0.05	1.41 ± 0.09	0.22 ± 0.05	34, 5	0.04, 0.02	[1]	1.28	4.43
HD 186427	5772 ± 25	4.40 ± 0.07	1.07 ± 0.04	0.08 ± 0.04	33, 7	0.03, 0.02	[4]	0.99	4.35
HD 187123	5845 ± 22	4.42 ± 0.07	1.10 ± 0.03	0.13 ± 0.03	30, 6	0.02, 0.03	[4]	1.04	4.33
HD 190228	5312 ± 30	3.87 ± 0.05	1.11 ± 0.04	−0.25 ± 0.05	35, 7	0.04, 0.02	[4]	–	–
HD 190228	5342 ± 39	3.93 ± 0.09	1.11 ± 0.05	−0.27 ± 0.06	37, 6	0.05, 0.04	[3]	–	–
HD 190228	5327	3.90	1.11	−0.26			avg.	–	–
HD 190360A	5584 ± 36	4.37 ± 0.06	1.07 ± 0.05	0.24 ± 0.05	29, 5	0.04, 0.02	[3]	0.96	4.32
HD 192263	4947 ± 58	4.51 ± 0.20	0.86 ± 0.09	−0.02 ± 0.06	35, 6	0.06, 0.10	[2]	0.69	4.51
HD 195019A	5859 ± 31	4.32 ± 0.07	1.27 ± 0.05	0.09 ± 0.04	39, 7	0.04, 0.03	[1]	1.06	4.18
HD 195019A	5836 ± 39	4.31 ± 0.07	1.27 ± 0.06	0.06 ± 0.05	35, 7	0.04, 0.03	[4]	1.05	4.16
HD 195019A	5842	4.32	1.27	0.08			avg.	1.06	4.17
HD 196050	5918 ± 44	4.35 ± 0.13	1.39 ± 0.06	0.22 ± 0.05	36, 7	0.04, 0.05	[1]	1.15	4.29
HD 202206[b]	5752 ± 53	4.50 ± 0.09	1.01 ± 0.06	0.35 ± 0.06	39, 6	0.05, 0.04	[1]	1.06	4.43
HD 209458	6117 ± 26	4.48 ± 0.08	1.40 ± 0.06	0.02 ± 0.03	34, 7	0.02, 0.03	[5]	1.15	4.41
HD 210277	5546 ± 28	4.29 ± 0.09	1.06 ± 0.03	0.21 ± 0.04	36, 6	0.04, 0.04	[2]	0.94	4.36
HD 210277	5519 ± 26	4.29 ± 0.18	1.01 ± 0.03	0.16 ± 0.04	34, 7	0.03, 0.08	[4]	0.91	4.34
HD 210277	5532	4.29	1.04	0.19			avg.	0.92	4.35
HD 213240	5984 ± 33	4.25 ± 0.10	1.25 ± 0.05	0.17 ± 0.05	38, 7	0.04, 0.04	[1]	1.22	4.18
HD 216435	5938 ± 42	4.12 ± 0.05	1.28 ± 0.06	0.24 ± 0.05	33, 6	0.04, 0.03	[1]	1.34	4.07
HD 216437	5887 ± 32	4.30 ± 0.07	1.31 ± 0.04	0.25 ± 0.04	37, 7	0.03, 0.03	[1]	1.20	4.21
HD 216770	5423 ± 41	4.40 ± 0.13	1.01 ± 0.05	0.26 ± 0.04	30, 7	0.04, 0.07	[4]	0.91	4.42
HD 217014	5804 ± 36	4.42 ± 0.07	1.20 ± 0.05	0.20 ± 0.05	35, 6	0.04, 0.02	[2]	1.05	4.36
HD 217107	5630 ± 32	4.28 ± 0.12	1.02 ± 0.04	0.37 ± 0.05	38, 7	0.04, 0.05	[1]	1.01	4.34
HD 217107	5663 ± 36	4.34 ± 0.08	1.11 ± 0.04	0.37 ± 0.05	37, 7	0.04, 0.03	[2]	1.02	4.36
HD 217107	5646	4.31	1.06	0.37			avg.	1.02	4.35
HD 219542B	5732 ± 31	4.40 ± 0.05	0.99 ± 0.04	0.17 ± 0.04	32, 7	0.03, 0.03	[4]	1.04	4.08
HD 222404	4916 ± 70	3.36 ± 0.21	1.27 ± 0.06	0.16 ± 0.08	26, 7	0.07, 0.08	[4]	–	–
HD 222582	5843 ± 38	4.45 ± 0.07	1.03 ± 0.06	0.05 ± 0.05	36, 7	0.04, 0.03	[3]	1.02	4.38

[a] The instruments used to obtain the spectra were: [1] 1.2-m Swiss Telescope/CORALIE; [2] 1.5-m and 2.2-m ESO/FEROS; [3] WHT/UES; [4] TNG/SARG; [5] VLT-UT2/UVES; [6] 1.93-m OHP/ELODIE; [7] Keck/HIRES.

[b] The companions to these stars have minimum masses above 10 $M_{\rm Jup}$, and are probably Brown-Dwarfs.

[c] These parameters, derived from a Keck/HIRES spectrum, were computed with a reduced number of iron lines. In the rest of the paper, only the parameters derived from the SARG/TNG spectrum were considered.

Smith 2003). In the next section we will present the results of a comparison between our spectroscopic and trigonometric gravities.

Finally, for a few stars we have stellar parameters and metallicities derived using different sets of spectra. A simple inspection of Tables 2–4 shows that the parameters derived from these different spectra are perfectly compatible with each other, within the errors.

3.1. Comparison with other works

To verify the quality of our results we have made a comparison with a number of different studies. In particular, we have compared the presented stellar parameters with the ones derived in our previous works (Papers II and III). This comparison reveals one main difference: the derived values for the surface gravity are now lower by about ~0.1 dex (on average). However,

Table 5. List of 41 stars from our comparison sample and derived stellar parameters. See text for more details.

HD number	$T_{\rm eff}$ [K]	$\log g_{\rm spec}$ [cm s^{-2}]	$\xi_{\rm t}$ [km s^{-1}]	[Fe/H]	N(Fe I, Fe II)	σ(Fe I, Fe II)	Instr.[a]	Mass [$M_\odot$]	$\log g_{\rm hipp}$ [cm s^{-2}]
HD 1581	5956 ± 44	4.39 ± 0.13	1.07 ± 0.09	−0.14 ± 0.05	33, 7	0.04, 0.05	[2]	1.00	4.41
HD 4391	5878 ± 53	4.74 ± 0.15	1.13 ± 0.10	−0.03 ± 0.06	35, 5	0.05, 0.05	[1]	1.11	4.57
HD 5133	4911 ± 54	4.49 ± 0.18	0.71 ± 0.11	−0.17 ± 0.06	38, 6	0.06, 0.09	[1]	0.63	4.49
HD 7570	6140 ± 41	4.39 ± 0.16	1.50 ± 0.08	0.18 ± 0.05	35, 6	0.04, 0.05	[1]	1.20	4.36
HD 10360	4970 ± 40	4.49 ± 0.10	0.76 ± 0.07	−0.26 ± 0.04	37, 5	0.05, 0.05	[1]	0.62	4.44
HD 10700	5344 ± 29	4.57 ± 0.09	0.91 ± 0.06	−0.52 ± 0.04	38, 6	0.03, 0.04	[1]	0.65	4.43
HD 14412	5368 ± 24	4.55 ± 0.05	0.88 ± 0.05	−0.47 ± 0.03	35, 6	0.03, 0.02	[1]	0.73	4.54
HD 17925	5180 ± 56	4.44 ± 0.13	1.33 ± 0.08	0.06 ± 0.07	35, 6	0.06, 0.06	[1]	0.84	4.58
HD 20010	6275 ± 57	4.40 ± 0.37	2.41 ± 0.41	−0.19 ± 0.06	33, 7	0.05, 0.14	[1]	1.33	4.03
HD 20766	5733 ± 31	4.55 ± 0.10	1.09 ± 0.06	−0.21 ± 0.04	37, 7	0.03, 0.04	[1]	0.93	4.51
HD 20794	5444 ± 31	4.47 ± 0.07	0.98 ± 0.06	−0.38 ± 0.04	39, 6	0.04, 0.03	[1]	0.72	4.38
HD 20807	5843 ± 26	4.47 ± 0.10	1.17 ± 0.06	−0.23 ± 0.04	37, 7	0.03, 0.04	[1]	0.94	4.45
HD 23249	5074 ± 60	3.77 ± 0.16	1.08 ± 0.06	0.13 ± 0.08	38, 5	0.07, 0.07	[1]	–	–
HD 23356	4975 ± 55	4.48 ± 0.16	0.77 ± 0.09	−0.11 ± 0.06	38, 6	0.06, 0.09	[1]	0.71	4.57
HD 23484	5176 ± 45	4.41 ± 0.17	1.03 ± 0.06	0.06 ± 0.05	38, 6	0.05, 0.08	[1]	0.82	4.55
HD 26965A	5126 ± 34	4.51 ± 0.08	0.60 ± 0.07	−0.31 ± 0.04	38, 5	0.04, 0.04	[1]	0.65	4.42
HD 30495	5868 ± 30	4.55 ± 0.10	1.24 ± 0.05	0.02 ± 0.04	37, 7	0.03, 0.04	[1]	1.10	4.54
HD 36435	5479 ± 37	4.61 ± 0.07	1.12 ± 0.05	−0.00 ± 0.05	38, 6	0.04, 0.04	[1]	0.98	4.60
HD 38858	5752 ± 32	4.53 ± 0.07	1.26 ± 0.07	−0.23 ± 0.05	37, 7	0.03, 0.02	[1]	0.91	4.47
HD 40307	4805 ± 52	4.37 ± 0.37	0.49 ± 0.12	−0.30 ± 0.05	37, 5	0.06, 0.20	[1]	–	–
HD 43162	5633 ± 35	4.48 ± 0.07	1.24 ± 0.05	−0.01 ± 0.04	34, 6	0.04, 0.03	[1]	1.00	4.57
HD 43834	5594 ± 36	4.41 ± 0.09	1.05 ± 0.04	0.10 ± 0.05	38, 5	0.04, 0.04	[1]	0.93	4.44
HD 50281A	4658 ± 56	4.32 ± 0.24	0.64 ± 0.15	−0.04 ± 0.07	34, 4	0.06, 0.12	[1]	–	–
HD 53705	5825 ± 20	4.37 ± 0.10	1.20 ± 0.04	−0.19 ± 0.03	36, 7	0.02, 0.03	[1]	0.93	4.31
HD 53706	5260 ± 31	4.35 ± 0.11	0.74 ± 0.05	−0.26 ± 0.04	35, 6	0.04, 0.05	[1]	0.78	4.57
HD 65907A	5979 ± 31	4.59 ± 0.12	1.36 ± 0.10	−0.29 ± 0.04	38, 7	0.03, 0.05	[1]	0.96	4.39
HD 69830	5410 ± 26	4.38 ± 0.07	0.89 ± 0.03	−0.03 ± 0.04	38, 7	0.03, 0.04	[1]	0.84	4.48
HD 72673	5242 ± 28	4.50 ± 0.09	0.69 ± 0.05	−0.37 ± 0.04	38, 6	0.03, 0.05	[1]	0.71	4.53
HD 74576	5000 ± 55	4.55 ± 0.13	1.07 ± 0.08	−0.03 ± 0.06	37, 5	0.06, 0.06	[1]	0.78	4.62
HD 76151	5803 ± 29	4.50 ± 0.08	1.02 ± 0.04	0.14 ± 0.04	39, 7	0.03, 0.05	[1]	1.07	4.50
HD 84117	6167 ± 37	4.35 ± 0.10	1.42 ± 0.09	−0.03 ± 0.05	35, 5	0.04, 0.04	[1]	1.15	4.34
HD 189567	5765 ± 24	4.52 ± 0.05	1.22 ± 0.05	−0.23 ± 0.04	37, 5	0.03, 0.02	[1]	0.89	4.39
HD 191408A	5005 ± 45	4.38 ± 0.25	0.67 ± 0.09	−0.55 ± 0.06	38, 4	0.05, 0.12	[1]	–	–
HD 192310	5069 ± 49	4.38 ± 0.19	0.79 ± 0.07	−0.01 ± 0.05	36, 6	0.05, 0.09	[1]	0.72	4.47
HD 196761	5435 ± 39	4.48 ± 0.08	0.91 ± 0.07	−0.29 ± 0.05	38, 5	0.04, 0.04	[1]	0.78	4.49
HD 207129	5910 ± 24	4.42 ± 0.05	1.14 ± 0.04	0.00 ± 0.04	37, 6	0.03, 0.02	[1]	1.04	4.42
HD 209100	4629 ± 77	4.36 ± 0.19	0.42 ± 0.25	−0.06 ± 0.08	36, 3	0.07, 0.06	[1]	–	–
HD 211415	5890 ± 30	4.51 ± 0.07	1.12 ± 0.07	−0.17 ± 0.04	35, 7	0.03, 0.02	[1]	0.97	4.42
HD 216803	4555 ± 87	4.53 ± 0.26	0.66 ± 0.28	−0.01 ± 0.09	30, 3	0.08, 0.10	[1]	–	–
HD 222237	4747 ± 58	4.48 ± 0.22	0.40 ± 0.20	−0.31 ± 0.06	37, 4	0.07, 0.11	[1]	–	–
HD 222335	5260 ± 41	4.45 ± 0.11	0.92 ± 0.06	−0.16 ± 0.05	35, 6	0.04, 0.05	[2]	0.77	4.52

[a] The instruments used to obtain the spectra were: [1] CORALIE; [2] FEROS.

for both the effective temperatures and metallicities, the differences are very small, not exceeding ∼10 k and 0.01 dex, respectively. In other words, the new parameters do not differ considerably in the main goal of our studies: the derivation of precise [Fe/H]. The changes we have made have not produced much of a difference in the obtained metallicities. This conclusion was expected, as it is well known that for solar-type dwarfs the abundances derived from the Fe I lines are mostly sensitive to the effective temperature (that did not vary much from our previous analysis to the current one) and are almost not dependent on surface gravity variations (see e.g. Paper I).

To verify this case we have performed a test where we used the solar equivalent widths (used to derive the $\log gf$ values) to obtain the effective temperature, microturbulence parameter, and metallicity for the Sun based only on the Fe I lines, and forcing the $\log g$ to a value of 4.54 dex, i.e., 0.1 dex above solar. The results were ($T_{\rm eff}$, $\xi_{\rm t}$, [Fe/H]) = (5755 K, 0.94 km s^{-1}, −0.01 dex), not very different to the "expected" solar values.

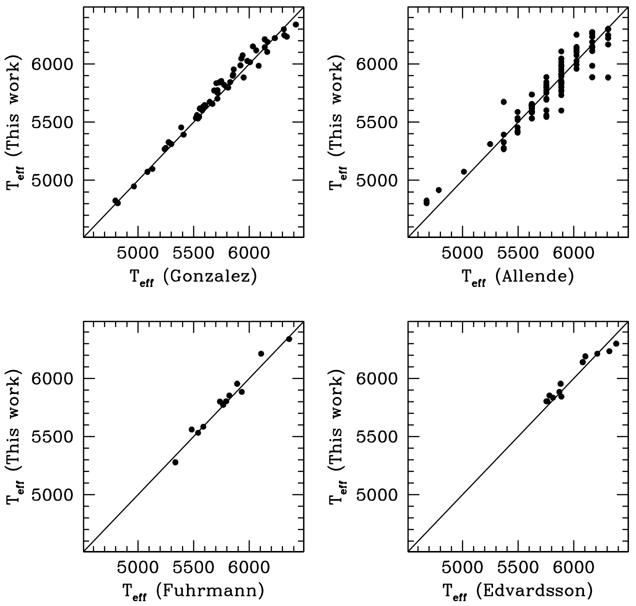

Fig. 1. Comparison of the $T_{\rm eff}$ values derived in this work with the ones obtained by other authors for the same stars. The solid line represents a 1:1 relation. See text for more details.

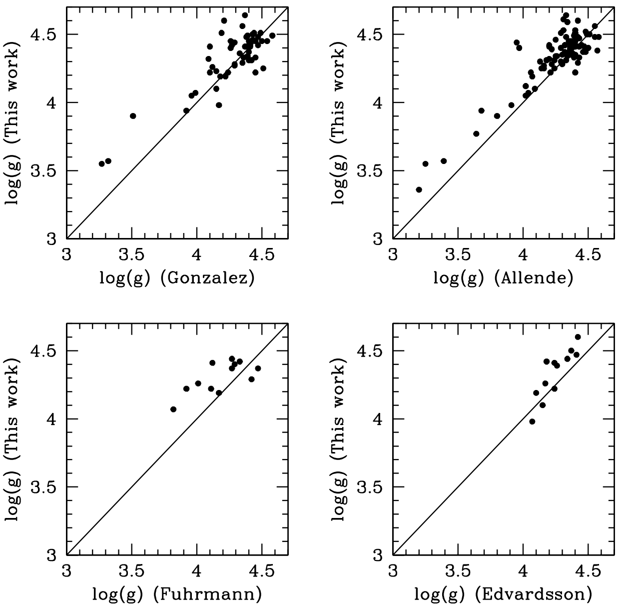

Fig. 2. Comparison of the spectroscopic $\log g$ values derived in this work with the ones obtained by other authors for the same stars. The solid line represents a 1:1 relation. See text for more details.

Similar or lower differences were obtained on a test done for the hotter dwarfs HD 82943 and HD 84177.

A clear conclusion of this analysis is that the method we used to derive stellar metallicities is not very dependent on errors in $\log g$.

3.1.1. Effective temperatures

We have further compared our stellar parameters with the ones derived by other authors for the stars in common.

For the $T_{\rm eff}$ we have found that our values are only +18 K in excess of those derived in the works of Fuhrmann et al. (1997, 1998), and Fuhrmann (1998), who used a H$_\alpha$ and H$_\beta$ line-fitting procedure to derive the effective temperatures (we have 12 stars in common) – see Fig. 1. Similarly, a small average difference of +25 K is found to the studies of Gonzalez et al. (2001), Laws et al. (2003), and references therein (57 stars; using a similar technique to ours), of +16 K to Edvardsson et al. (1993) (12 stars; $T_{\rm eff}$ derived from photometry), and of −2 K to Allende Prieto & Lambert (1999) (90 stars; these authors used an evolutionary model-fitting procedure to derive the stellar parameters). An insignificant average difference of 3 K is also found when comparing our results with the values obtained by Ribas et al. (2003), based on IR photometry.

3.1.2. Surface gravities

For surface gravities, we have also found small differences to the other studies, (when compared with the individual errors or the order of 0.12 dex) – see Fig. 2. In particular, our $\log g$s are only ~0.05 dex (on average) above the ones derived by Gonzalez et al. (2001), Laws et al. (2003), and references therein, and 0.08 dex above the results of Allende Prieto & Lambert (1999), and Edvardsson et al. (1993) (i.e., differences of the order of 1–2%). This difference is even smaller (below 0.04 dex, when compared with the results of the Gonzalez group) if we do not consider the most evolved stars. A slightly higher difference of about +0.10 dex is also found to the works of Fuhrmann et al. (1997, 1998), and Fuhrmann (1998); these authors had already found that their spectroscopic gravities were lower than trigonometric-based parallaxes by about 0.03 dex.

If we compare the spectroscopic surface gravities with the $\log g$ computed using the derived stellar masses (Fig. 3), the spectroscopic effective temperatures and the Hipparcos parallaxes (see above), the average difference we obtain is ~0.03 dex (spectroscopic gravities being higher), i.e. about 1% – see Fig. 3[6]. This difference is slightly higher for lower metallicity stars ([Fe/H] < −0.2 dex), reaching 0.06 dex, and smaller for the remaining objects (around 0.02 dex). The same "gradient" is seen if we analyze planet hosts and comparison sample stars separately. Such a difference might in fact reflect non-LTE effects on Fe I lines (Thévenin & Idiart 1999), and will be explored in more detail in a future paper.

Interestingly, however, planet hosts have higher $\log g_{\rm spec} - \log g_{\rm hipp}$ (by ~0.04 dex), even though they are on average more metal-rich by ~0.25 dex. This same result was also noticed by Laws et al. (2003), and is opposite to the effect expected if the excess metallicity observed for planet host stars were of external origin (Ford et al. 1999).

An explanation for this latter inconsistency might be related to the fact that planet-host stars are, on average, hotter than our comparison sample objects by about 200 K. Indeed, an analysis of our results shows a trend, of the order of 0.1 dex/1000 K, in the sense that higher $T_{\rm eff}$ stars also have higher than

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[6] Such differences are equivalent to errors of 7% in the stellar mass, of 3% in the distance, or of 1–2% in the effective temperature.

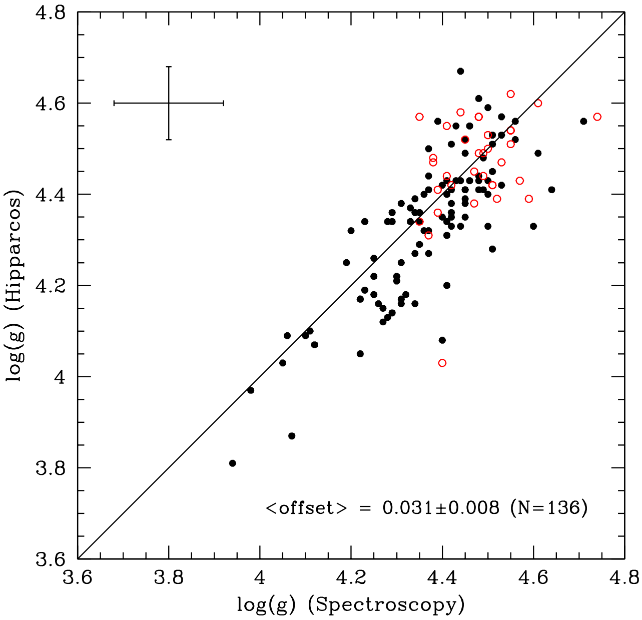

Fig. 3. Comparison of the spectroscopic and parallax based surface gravities of our program stars. Filled symbols represent planet-host stars, while open symbols denote stars from our comparison sample. The error bars represent typical relative errors in both axis. The solid line represents a 1:1 relation.

average $\log g_{\mathrm{spec}} - \log g_{\mathrm{hipp}}$. A comparison of our surface gravities with the ones of Laws et al. (2003) and Allende Prieto & Lambert (1999) does not reveal such a clear slope, while a comparison of the values of the $\log g_{\mathrm{spec}}$ and $\log g_{\mathrm{evol}}$ derived by Laws et al. (2003) also shows the very same trend with effective temperature. These results suggest that the problem might be related to the determination of the trigonometric $\log g$ values (or else, all the three works have the same bias). Sources of errors might include systematics in the bolometric corrections, perhaps related to the fact that the calibration of Flower (1996) used does not include a metallicity dependence (see e.g. Cayrel et al. 1997), or errors in the isochrones used to compute the stellar masses (see e.g. Lebreton et al. 1999)[7]. The trend could also reflect NLTE errors (although we caution that differential NLTE effects for stars with different temperature should not be very important for solar-type dwarfs (see e.g. Bensby et al. 2003)), erroneous atomic line parameters, or problems in the stellar atmosphere models for different effective temperatures.

Since the derived [Fe/H] values are not very sensitive to the obtained $\log g$ (see above), this result does not affect the derivation of accurate stellar metallicities.

3.1.3. [Fe/H]

Finally, and most importantly, we have compared our spectroscopic metallicities with the ones listed in all the studies mentioned above (Fig. 4). The average differences found are always between −0.01 and +0.01 dex, being higher only for the study Edvardsson et al. (1993) (0.06 dex, our results being above). In general, this difference is also not a function of the metallicity of the stars, i.e., within the errors it represents a uniform shift. The only marginal trend appears when comparing our metallicities with the ones derived by Fuhrmann et al., in the sense that their estimates are above ours for the more metal-rich stars, and below for the metal-poor objects.

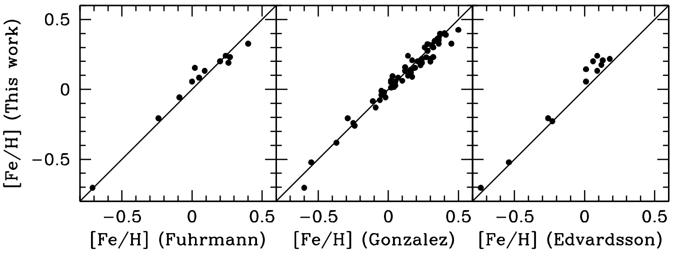

Fig. 4. Comparison of the [Fe/H] values derived in this work with the ones obtained by other authors for the same stars. The solid line represents a 1:1 relation. See text for more details.

The results we have obtained are thus perfectly compatible with other precise published values.

4. Other planet-host stars

For a few planet-host stars (BD−10 3166, HD 41004A, HD 104985B, and GJ 876) we could not gather spectra and derive our own metallicities and stellar parameters. We have thus tried to find values of the metallicities for these stars in the literature. For HD 41004A, however, there were no published spectroscopic metallicity estimates available, and we have decided to obtain stellar metallicities using another technique.

As used by several authors (e.g. Mayor 1980; Pont 1997; Santos et al. 2002), the surface of the Cross-Correlation Function (CCF) yields precise metallicity estimates of a star. Santos et al. (2002) (see their Appendix) have used this method to derive a relation between [Fe/H], $B-V$, and the surface of the CCF of the CORALIE spectrograph (hereafter W_{fit}). This relation is now revised to take into account the slight change in the metallicity scale introduced here, as well as metallicity estimates for new stars. The result gives:

$$\begin{aligned}[\mathrm{Fe/H}] &= 2.7713 + 4.6826 \log W_{\mathrm{fit}} - 8.6714\,(B-V) \\ &\quad +3.8258\,(B-V)^2 \end{aligned} \tag{2}$$

a calibration valid for dwarfs with $0.52 < B-V < 1.09$, $1.26 < W_{\mathrm{fit}} < 3.14$, and $-0.52 < [\mathrm{Fe/H}] < 0.37$. We note that the use of this relation to obtain values of metallicities for stars that are out of the domain of this calibration (by a small amount) should not be of much concern, since it is expected to be a linear function of W_{fit}. On the other hand, we believe it is not wise to extrapolate this relation for other spectral types, as the dependency in T_{eff} is much stronger and unpredictable. This calibration has an rms of only 0.06 dex ($N = 92$), similar to the typical errors of the spectroscopic estimates of [Fe/H]. We refer the reader to Santos et al. (2002) for more details regarding this technique.

HD 6434 was earlier reported by Laws et al. (2003) to occupy a strange position in the HR diagram. Curiously, when calibrating the relation expressed in Eq. (2), HD 6434 was not

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[7] Errors in the bolometric correction should not have a significant influence on the derived stellar masses.

Table 6. Candidate planet-host stars for which we could not obtain a spectrum at the time of the publication of this paper. The stellar metallicities and effective temperatures have been taken from various sources. For HD 41004A, the effective temperature has been derived using Eq. (A.1) and $B-V$ taken from the Hipparcos catalog (ESA 1997).

Star	$T_{\rm eff}$ [K]	[Fe/H]	Source of [Fe/H]
BD−10 3166	5320	0.33	Gonzalez et al. (2001)
HD 41004A	5085	0.05	CORALIE CCF (Eq. (2))
HD 104985B†	4786	−0.35	Sato et al. (2003)
GJ 876	3100–3250	Solar	Delfosse et al. (1998)

† This star is a giant.

included, as it was the only star falling significantly out of the trend in the residuals of the fit. Preliminary results of a recent adaptative optics survey did not show the presence of any close companion to this star (Eggenberger, private communication). We do not have any explanation for the observed discrepancy.

In Table 6 we list the stellar metallicities gathered for the stars referred above, together with their sources. For GJ 876 alone we could not find precise metallicity estimates, as this star is an M-dwarf.

We caution that only for BD−10 3166, whose parameters were taken from the works of the Gonzalez team, can we be sure that the [Fe/H] values are in the same scale as ours. The same is true for HD 41004A, whose [Fe/H] value was derived from Eq. (2). For different reasons we have chosen not to include any of these in our further analysis: BD−10 3166 because it was searched for planets due to its high metal content and HD 41004A because its spectrum is a blend of a K and M dwarfs (Santos et al. 2002), and thus its derived metallicity must be taken as an approximate value.

5. Confirming the metal-rich nature of planet-host stars

Having gathered metallicities for almost all known exoplanet hosts, we will now review the implications of the available sample for the study of the metallicities of planet-host stars. For an extensive discussion about the subject we point the reader to our previous Papers II and III. The main difference between the current results and the ones published in these papers are quantitative; the qualitative results are similar.

5.1. The global trend

In the upper panels of Fig. 6 we present a comparison between the metallicity distributions for our volume-limited comparison sample of stars (Table 5) and for the planet-host stars with available detailed spectroscopic metallicities. For this latter sample, we have excluded those stars that were searched for planets based on their high metallicity (we refer to Paper III for more details and references). We are left with 41 stars in our comparison sample, and with 93 planet-hosts.

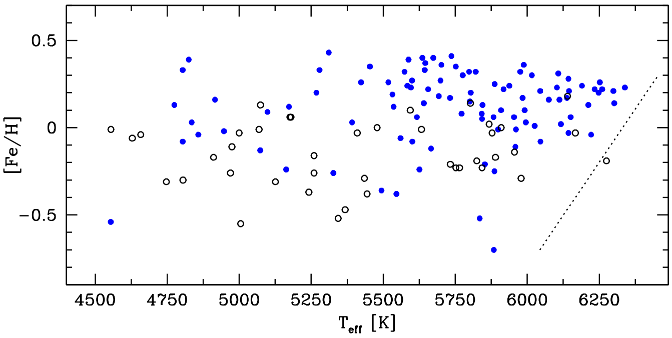

Fig. 5. Metallicity as a function of the effective temperature for planet hosts (filled dots) and comparison sample stars (open circles). The dotted line represents the approximate lower limit in $B-V$ of the CORALIE planet search sample (Udry et al. 2000), as based on Eq. (A.1) (for $B-V$ = constant = 0.5).

A look at the two upper panels clearly shows that planet-hosts are considerably metal-rich compared to the comparison sample stars by, on average, 0.25 dex. According to a Kolmogorov-Smirnov test, these two samples have a probability of only 1.6×10^{-9} of belonging to the same population. The results obtained with the new spectroscopic analysis strongly confirm all the most recent results on this subject (e.g. Santos et al. 2001, 2003a; Gonzalez et al. 2001; Reid 2002; Laws et al. 2003), that show that stars with planets are more metal-rich than average field dwarfs.

An analog of Fig. 5 (where we plot the stellar metallicity as a function of $T_{\rm eff}$) was used by several authors (e.g. Pinsonneault et al. 2001; Santos et al. 2001, 2003a; Gonzalez et al. 2001) to try to decide whether the excess metallicity observed in planet-host stars is of "primordial origin" (corresponding to the metallicity of the cloud that formed the star/planet system) or of external origin (reflecting the infall of iron-rich planetary material into the stellar convective envelope). Although here we will not discuss this in much detail (we refer to Paper III, Israelian et al. 2003, and Gonzalez et al. 2003 for a comprehensive discussion), the plot of Fig. 5, showing that the excess metallicity found for planet hosts is real and "constant" for all the $T_{\rm eff}$ regimes, seems to support the former scenario. We should mention, however, that recent results by Vauclair (2003) suggest that this conclusion might not be straighforward; other evidence exist, however, supporting the promordial origin of the metallicity excess observed – see Papers II and III.

As already noted e.g. in Papers II and III, a look at this figure also shows that the upper envelope of the planet-host metallicities is a slight decreasing function of the stellar effective temperature. Although not clear, this result may be related to the presence of NLTE effects on iron lines for stars at different effective temperatures (Thévenin & Idiart 1999), but differential NLTE effects on iron lines might be relatively small in this temperature interval (Bensby et al. 2003).

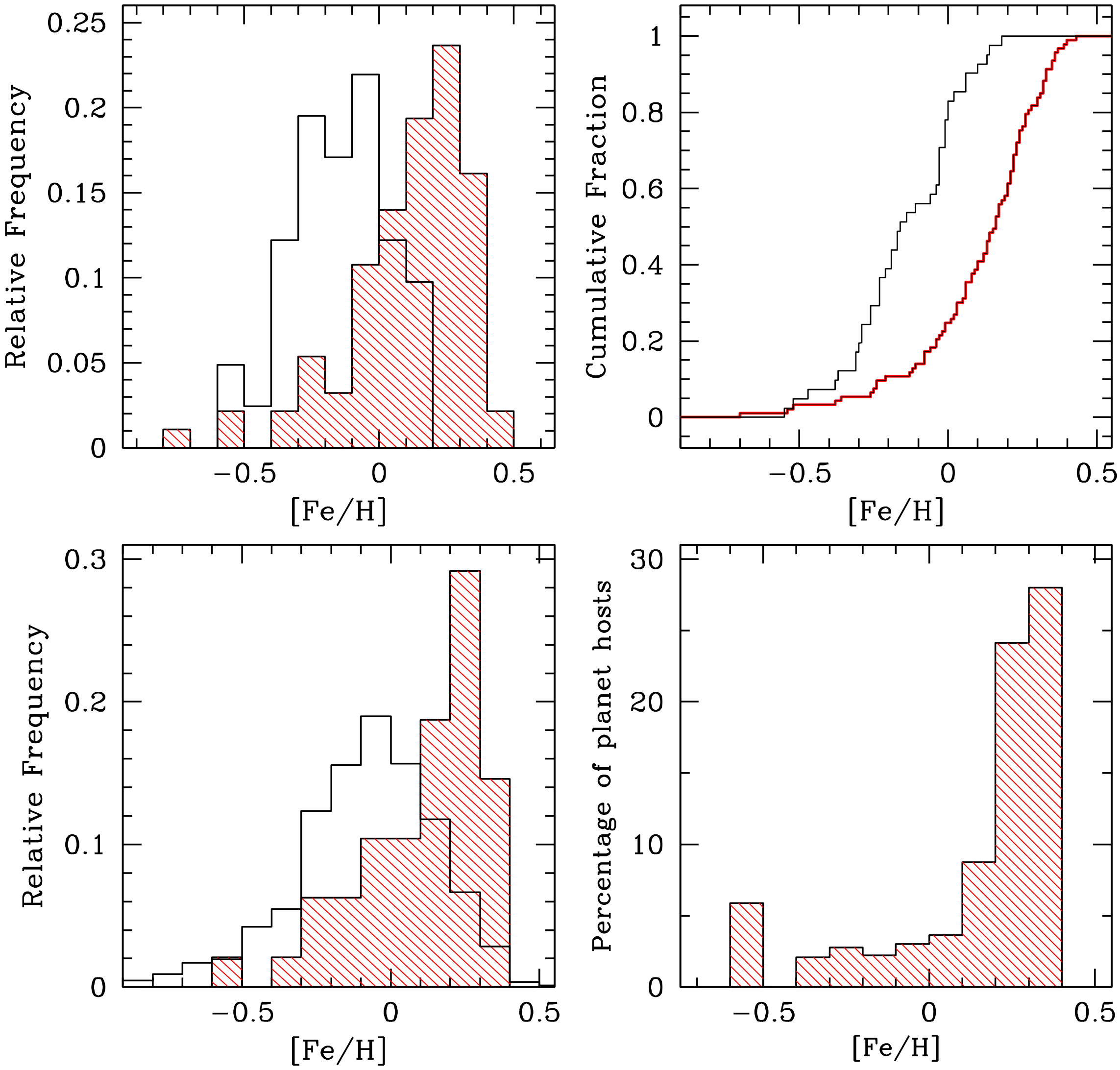

Fig. 6. *Upper panels*: [Fe/H] distributions for planet host stars (hashed histogram) and for our volume-limited comparison sample of stars (open bars). The average difference between the [Fe/H] of the two samples is of ~0.25 dex. A Kolgomorov-Smirnov test shows that the probability that the two samples are part of the same population is of the order of 10^{-9}. See text for more details. *Lower panel, left*: [Fe/H] distributions for planet host stars (hashed histogram) included in the CORALIE planet-search sample, when compared with the same distribution for all the 875 stars in the whole CORALIE program for which we have at least 5 radial-velocity measurements (solid-line open histogram). *Lower panel, right*: percentage of planet hosts found amid the stars in the CORALIE sample as a function of stellar metallicity.

5.2. Planet frequency as a function of stellar metallicity

In Fig. 6 (lower-left panel) we compare the metallicity distribution of the 48 planet-host stars that were found amid the dwarfs in the CORALIE (volume-limited) planet search sample[8] (Udry et al. 2000) with the [Fe/H] distribution for the objects in the CORALIE sample for which we have gathered at least 5 radial-velocity measurements (solid line histogram). The metallicities for this large sample have been obtained using Eq. (2), and are thus in the same scale as the values obtained with our detailed spectroscopic analysis. This sub-sample is built up of stars for which we should have found a giant planet, at least if it had a short period orbit.

This "comparison" distribution give us the opportunity to derive the frequency of planets as a function of stellar metallicity for the stars in the CORALIE sample. Such a result is presented in Fig. 6 (lower-right panel). The figures tells us that the probability of finding a planet is a strong function of the stellar metallicity. About 25–30% of the stars with [Fe/H] above 0.3 have a planet. On the other hand, for stars with solar metallicity this percentage is lower than 5%. These numbers thus confirm previous qualitative results on this matter (see Papers II and III, and articles by Reid (2002) and Laws et al. (2003); similar results were also recently presented by D. Fischer at the IAU219 symposium, regarding an analysis of the Lick planet survey sample). We note that in Paper III, the percentage values in Fig. 2 are wrong by a constant factor; however, the results are qualitatively the same – see also Paper II.

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[8] These include the stars listed in footnote 7 of Paper III plus HD 10647, HD 65216, HD 70642, HD 73256, HD 111232, HD 142415, and HD 216770.

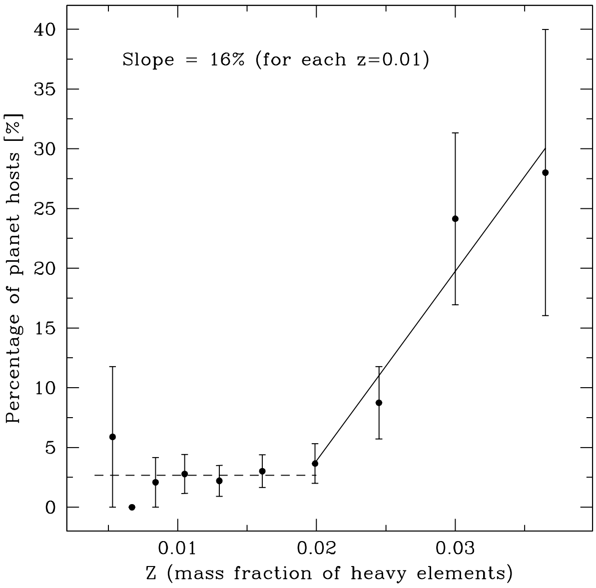

Fig. 7. Percentage of planet hosts for the plot in Fig. 6 (lower-right panel, hashed histogram) as a function of the mass fraction of heavy elements (an increasing function of [Fe/H]). Error bars are approximate values based on Gaussian statistics. The plot suggests that the percentage is relatively constant for $Z < 0.02$ (solar), increasing then linearly for higher Z values, with an increase of 16% for each $\Delta Z = 0.01$.

The exact percentages discussed above depend mainly on the sub-sample of stars in the CORALIE survey used to compute the frequencies. Current values can only be seen as lower limits, and the true numbers will only be known when the survey is closer to the end (although the order of magnitude is probably the one presented here). Only then will we also be able to provide plots regarding e.g. stars having planets with different orbital properties and masses (e.g. orbital period). But present day results suggest that there are no strong and clear correlations between stellar metallicity and the planetary parameters (see e.g. Paper III).

The main interest here resides in the qualitative, rather than in the quantitative result. The crucial conclusion is that more metal-rich stars seem to form planets more easily (and/or more planets?) than their lower-[Fe/H] counterparts. The dependence seems to be very steep, as illustrated in Fig. 6. The probability of forming a planet seems to be a strong function of the metallicity of the proto-planetary disk. This result, valid at least for the kind of planets that are now being discovered, has enormous implications for the theories of planetary formation and evolution (see Paper III for an extensive discussion on this subject), as well as on studies of the frequency of planets in the galaxy (e.g. Lineweaver 2001).

5.3. A flat metallicity tail?

In Fig. 6 (lower-right panel), for [Fe/H] < 0.0 dex ($Z < 0.02$), we have the impression that the corrected distributions are rather flat (see also Fig. 7). Although it is probably too early to make a definite conclusion, if confirmed this could imply that the probability of forming a planet is reasonably constant for metallicities up to about the solar value, and only then, there is some kind of "runaway" process that considerably enhances the efficiency of planetary formation.

In Fig. 7 we plot the percentage of known planets as a function of stellar Z (the mass fraction of heavy elements). The plot also reflects the flatness of the distribution for metallicities below solar ($Z < 0.02$), and an increase for higher values. Curiously, for $Z > 0.02$ the percentages seem to be linearly related to Z, with a slope of ~16% for each $\Delta Z = 0.01$.

One possibility to explain these trends would be to consider that these reflect the presence of two distinct populations of exoplanets (something already discussed in Paper III and Gonzalez et al. 2003), formed by different processes: one of them not dependent on the metallicity (e.g. disk instability – Boss 2002; Mayer et al. 2002), producing a constant minimum number of planets as a function of [Fe/H], together with another very metallicity-dependent (a process such as core accretion – Pollack et al. 1996). In this context, we have searched for possible differences in the properties of the planets orbiting stars in different metallicity regimes (eccentricity, period, masses). Nothing statistically significant is found (see Paper III and Laws et al. 2003). In particular, no clear differences in the mass distributions for the planetary companions seem to exist regarding stars with [Fe/H] < 0.0 and [Fe/H] > 0.0. If indeed we were seeing two different populations of planets, such differences could be expected, as disk instability processes should be able to form preferentially higher mass planets (opposite to the core-accretion) – (see e.g. Rice et al. 2003). We note, however, that a slight trend in the opposite sense is found (see Paper III), i.e., lower metallicity stars seem to harbor preferentially lower mass planets.

A recent work by Rice & Armitage (2003) has pointed out that giant planets might be formed in relatively metal-poor disks by the traditional core-accretion model (although at lower probabilities), in a timescale compatible with the currently accepted disk lifetimes. Indeed, core-accretion models have been usually criticized because they predict that the formation of a giant planet could take longer than the estimated lifetimes of T-Tauri disks (e.g. Haisch et al. 2001). Recent developments have, however, put new constraints on the disk lifetimes that may be considerably longer than previously predicted (Bary et al. 2003). Furthermore, according to Rice & Armitage (2003) the disk lifetimes might not be a problem at all. The key to this are turbulent fluctuations in the protoplanetary disk, inducing a "random walk" migration, that accelerates the formation of the giant planet (Rice & Armitage 2003). If true, this result might explain the existence of giant planets around mildly metal-poor stars, as observed. However, the work of Rice & Armitage does not tell us much about the observed trends, and in particular about the possible flatness observed in the corrected metallicity distribution for values below about solar. Instead, it implies that disk-instability models are probably not needed to explain the presence of giant planets around the most metal-poor stars in our sample.

Note that the lowest metallicity bin of the plots is based on only one planet-host, and is thus not statistically significant.

6. Concluding remarks

In this paper we have derived stellar metallicities from a detailed spectroscopic analysis of a sample of 98 stars known to be orbited by planetary mass companions, as well as for a volume-limited sample of stars not known to host any planets. The main results are:

- The obtained stellar parameters ($T_{\rm eff}$, $\log g$, [Fe/H], and stellar masses) are compatible, within the errors, with the values derived by other authors using similar or different techniques. In particular, the derived surface gravities are only on average ~0.03 dex different to trigonometric estimates based on Hipparcos parallaxes.
- We confirm the previously known trends that stars with planets are more metal-rich than average field dwarfs. The average difference is of the order of 0.25 dex.
- We confirm previous results (e.g. Papers II and III) that have shown that the frequency of stars having planets is a strong rising function of the stellar metallicity. About 25–30% of dwarfs in the CORALIE planet search sample having [Fe/H] > 0.3 harbor a planetary companion. This number falls to ~3% for stars of solar metallicity. The Sun is in the tail of this distribution, that seems to be rather flat for [Fe/H] < 0.0 (i.e. for mass fractions of heavy elements $Z < 0.02$), but increasing (maybe linearly) as a function of Z for higher values. Possible implications of these results are discussed.

The main conclusions of this paper agree with previous results that have investigated the striking role that stellar metallicity seems to be playing in the formation of giant planets, or at least in the formation of the kind of systems "planet-hunters" are finding now. However, it is crucial that this kind of analysis is done on a continuous basis as new planets are added to the lists. In particular, the question of knowing whether the Solar System is typical is particularly troubling, as the Sun falls in the tail of the [Fe/H] distributions of planet-host stars.

Acknowledgements. We would like to thank Nami Mowlavi for the important help in determining the stellar masses, David James for obtaining spectra for 3 of our targets, as well as to P. Bartholdi, S. Udry, F. Pont, D. Naef, and S. Jorge for fruitful discussions. We wish to thank the Swiss National Science Foundation (Swiss NSF) for the continuous support for this project. Support from Fundação para a Ciência e Tecnologia (Portugal) to N.C.S. in the form of a scholarship is gratefully acknowledged.

Appendix A: A calibration of $T_{\rm eff}$ as a function of $B-V$ and [Fe/H]

We have used the derived spectroscopic $T_{\rm eff}$ and [Fe/H] as well as Hipparcos $B-V$ colors (ESA 1997) to derive a new calibration of the effective temperature as a function of $B-V$ and [Fe/H]. The result, also illustrated in Fig. A.1, is:

$$\begin{aligned} T_{\rm eff} &= 8423 - 4736\,(B-V) + 1106\,(B-V)^2 \\ &\quad +411\,[{\rm Fe/H}] \qquad \text{(A.1)} \end{aligned}$$

valid for stars with $\log g > 4.0$ in the range of $0.51 < B-V < 1.33$, $4495 < T_{\rm eff} < 6339$ K, and $-0.70 <$ [Fe/H] < 0.43. The rms of the fit is only of 43 K, illustrating the quality of the relation. We can use this calibration to derive reliable temperatures for our stars, whenever a detailed spectroscopic analysis is not possible, with the guarantee that the resulting values will be in the same $T_{\rm eff}$ scale.

In Fig. A.2 we compare the effective temperatures derived from Eq. (A.1) with the ones obtained from a similar

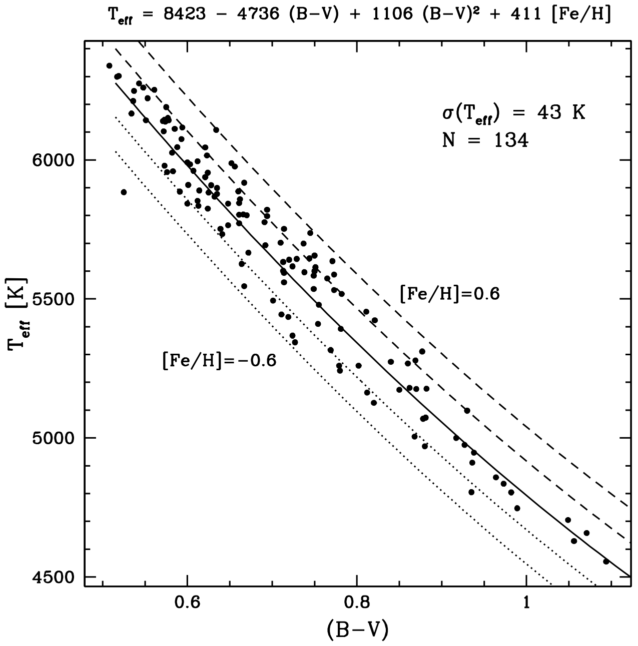

Fig. A.1. Calibration of the $T_{\rm eff}$ as a function of $B-V$ and [Fe/H]. The 5 "fitted" lines represent lines of constant [Fe/H] (in steps of 0.3 dex).

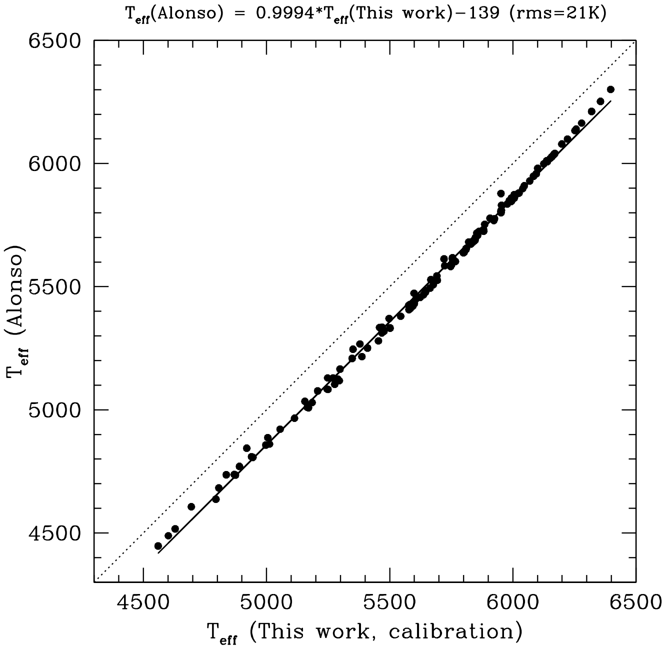

Fig. A.2. Comparison between the effective temperatures derived from our calibration and the one of Alonso et al. (1996). The dotted line represents a 1:1 relation while the solid line is a linear fit to the points.

calibration presented by Alonso et al. (1996) for all the stars in our sample. A fit to the data gives:

$$T_{\rm eff}^{\rm Alonso} = 0.9994\,T_{\rm eff}^{\rm This\ work} - 139 \qquad \text{(A.2)}$$

Except for the presence of a constant offset (reflecting different temperatures scales), the fit is remarkably good, having a dispersion of only 21 K.

Note added in proof: After the acceptance of this paper, new extra-solar planets have been announced orbiting the giant stars HD 59686 and HD 219449 (Mitchell et al., BAAS, 35 Nr.5, #17.03).

In Sect. 5.3 we discuss the results of a paper by Rice & Armitage concerning the turbulence induced stochastic migration mechanisms, and the role these might have to decrease the timescales for planet accretion. In this discussion we should have also mentioned that the ideas about stochastic migration were discussed in a recent paper by Nelson & Papaloizou (2003, MNRAS, in press – [`astro-ph/0308360`]).

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