A&A 474, 647–651 (2007)
DOI: 10.1051/0004-6361:20078129

Astronomy
&
Astrophysics

The HARPS search for southern extra-solar planets[⋆]

XII. A giant planet orbiting the metal-poor star HD 171028

N. C. Santos[1,2], M. Mayor[2], F. Bouchy[3], F. Pepe[2], D. Queloz[2], and S. Udry[2]

[1] Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
e-mail: `nuno@astro.up.pt`
[2] Observatoire de Genève, 51 Ch. des Maillettes, 1290 Sauverny, Switzerland
[3] Institut d'Astrophysique de Paris, UMR7095 CNRS, Université Pierre & Marie Curie, 98bis Bd Arago, 75014 Paris, France

Received 21 June 2007 / Accepted 7 August 2007

ABSTRACT

In this paper we present the detection of a 1.8 $M_{\rm Jup}$ planet in a 538-day period trajectory orbiting the metal-poor star HD 171028 ([Fe/H] = −0.49). This planet is the first to be discovered in the context of a HARPS program searching for planets around metal-poor stars. Interestingly, HD 171028 is one of the least metal-poor stars in the sample. This discovery is placed in the context of the models of planet formation and evolution.

Key words. stars: planetary systems – planetary systems: formation – techniques: radial velocity – stars: abundances

1. Introduction

The discovery of more than 220 extra-solar planets orbiting solar-type stars[1] is providing crucial evidence for the processes of planet formation and evolution (for a review see Udry & Santos 2007). Among these, important clues come from the study of planet-host stars. The well known strong correlation between the presence of giant planets and the stellar metallicity (Gonzalez 1997; Gonzalez et al. 2001; Santos et al. 2001, 2004b, 2005; Reid 2002; Fischer & Valenti 2005) suggests that giant planets are more easily formed around higher metal-content stars. This lends supports to the core-accretion model (Mizuno 1980; Pollack et al. 1996) as the main planet formation mechanism (Ida & Lin 2004b; Benz et al. 2006), in contrast to the alternative disk-instability model (Boss 1997, 2002; Mayer et al. 2002).

The higher probability of finding giant planets orbiting metal-rich stars prompted a number of different surveys dedicated to metal-rich samples (Tinney et al. 2002; Fischer et al. 2005; da Silva et al. 2006b; Melo et al. 2007). Given their observing strategy, these programs unveiled mostly short period planets, strongly biasing the known samples, while positively increasing the number of detected transiting planets orbiting bright stars (e.g. Sato et al. 2005; Bouchy et al. 2005b).

Interestingly however, several giant planets were found to orbit metal-poor stars, with down to ∼2 times fewer metals than the Sun (Setiawan et al. 2003; Mayor et al. 2004; Cochran et al. 2007). Some programs to search for planets around such objects were also started. Two of these include the use of the Keck and HET telescopes (Sozzetti et al. 2006; Cochran et al. 2007, respectively). A third one, presented in this paper, is part of the HARPS GTO planet search program (Mayor et al. 2003).

Part of the goal of these programs is to try to understand how frequent giant planets orbiting metal-poor stars are, and to determine the metallicity limit below which no giant planets can be observed. Such constraints would give important new clues about the processes of planet formation and evolution (e.g. Matsuo et al. 2007). The recent finding that the metallicity correlation may no longer be valid for Neptune-mass planets (see HD 4308 ([Fe/H] = −0.31) and discussion in Udry et al. 2006), together with theoretical predictions suggesting that very low mass planets may be common around metal-poor stars (Ida & Lin 2004a; Benz et al. 2006), renewed the interest for these surveys.

In this paper we present the first detection of a giant planet orbiting one star from the HARPS metal-poor stars survey. The planet orbits HD 171028 ([Fe/H] = −0.49) in a 538-day period orbit. In Sect. 2 we describe the sample used. In Sect. 3 we present the observations of HD 171028, providing the stellar parameters and the orbital solution found. We conclude in Sect. 4.

2. The HARPS metal-poor sample

The HARPS GTO program started to follow several different samples of solar-type stars in October 2003 (Mayor et al. 2003). The remarkable long term precision of HARPS allowed the discovery of several planets among the targets (Pepe et al. 2004; Lovis et al. 2005), including the large majority of the known planets with masses of the order of the mass of Neptune or below (Santos et al. 2004a; Bonfils et al. 2005, 2007; Lovis et al. 2006; Udry et al. 2006, 2007).

To explore the low metallicity tail of the planet-host stars distribution, one of the samples currently studied with HARPS is constituted of 105 metal-poor or mild metal-poor solar-type stars. This sample was chosen based on the large FGK-catalogue of Nordström et al. (2004). From this catalogue, we took all late-F, G, and K stars ($b-y > 0.330$) south of +10° of declination and having a visual V magnitude brighter than 12. From

---

[⋆] Based on observations collected at the La Silla Parana Observatory, ESO (Chile) with the HARPS spectrograph at the 3.6 m telescope, under the GTO program 072.C-0488.

[1] See e.g. table at `http://www.exoplanets.eu/`

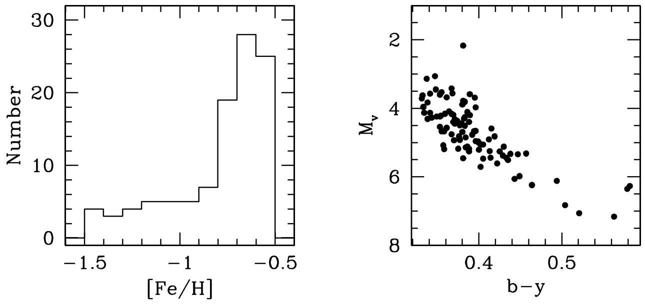

Fig. 1. *Left*: metallicity distribution for the whole HARPS metal-poor sample (photometrically derived metallicities). *Right*: M_v vs. $b - y$ diagram for the stars in the sample.

these we then excluded all known visual and spectroscopic binaries, all stars suspected to be giants, and all those with measured projected rotational velocity $v \sin i$ above ~6.0 km s^{-1} (to indirectly exclude the most active stars). Finally, we considered only those targets with photometric [Fe/H] between −0.5 and −1.5.

In Fig. 1 we plot the metallicity distribution of the sample, as well as a M_v vs. $b - y$ diagram. The distribution clearly peaks between −0.5 and −0.8, while a long "flat" metallicity tail is present down to [Fe/H] = −1.5. We note that HD 171028 (spectroscopic metallicity of −0.49) was only included in the catalogue because its photometric metallicity is lower than this value (see discussion in the next section).

The final 105 stars in the sample have their *V* magnitudes between 5.9 and 10.9, distributed around an average value of 8.7. After a 15-min exposure these magnitudes allow us to obtain a *S/N* high enough to derive radial-velocities with a precision better than 1 m s^{-1} for the majority of the targets.

3. A new planet around HD 171028

3.1. Observations

We obtained a total of 19 measurements of HD 171028 in GTO time (program ID 072.C-0488) using the HARPS spectrograph (3.6-m ESO telescope, La Silla, Chile). The observations were carried out between October 2004 and April 2007, and the radial-velocities were obtained using the latest version of the HARPS pipeline. We refer to Pepe et al. (2004) for details on the data reduction.

Exposure times varied between 260 and 900 s, and the individual photon-noise error in the radial-velocities was always below 1.7 m s^{-1} (median of 0.8 m s^{-1}). In this error we do not quantify the uncertainties due to the stellar oscillation modes (Bouchy et al. 2005a). This "noise" is typically averaged out if a long (15-min) exposure is performed. Unfortunately, this was not always the case when observing HD 171028 (only 12 out of the 19 measurements follow this strategy).

The individual spectra were also used to derive both the Bisector Inverse Slope (BIS) of the HARPS Cross-Correlation Function (CCF), as defined by Queloz et al. (2000), as well as a measurement of the chromospheric activity index $\log R'_{\rm HK}$, following a similar recipe as used by Santos et al. (2000) for CORALIE spectra. Finally, the combined high *S/N* HARPS spectra were analyzed to derive stellar atmospheric parameters and iron abundances using the method described in Santos et al. (2004b).

Table 1. Stellar parameters for HD 171028.

Parameter	Value	Reference
Spectral type	G0	Simbad
m_v	8.31	Simbad
$B - V$	0.61	Simbad
$b - y$	0.43	Nordström et al. (2004)
$\log R'_{\rm HK}$	−4.92†	This paper
Distance [pc]	90	This paper
$v \sin i$ [km s^{-1}]	2.3††	This paper
$T_{\rm eff}$ [K]	5663 ± 20	This paper
$\log g$	3.84 ± 0.05	This paper
$\xi_{\rm t}$	1.32 ± 0.05	This paper
[Fe/H]	−0.49 ± 0.02	This paper
Mass [$M_\odot$]	0.99±0.08	This paper

† From HARPS spectra using a calibration similar to that presented by Santos et al. (2000). †† From HARPS spectra using a calibration similar to that presented by Santos et al. (2002).

3.2. Stellar characteristics

Little information is available about HD 171028 (BD+06 3833, $V = 8.31$, $B-V = 0.61$), and only two papers appear in a Simbad query (Olsen 1994; Nordström et al. 2004). The star is also not in the Hipparcos catalogue (ESA 1997), and most of the information available on the Tycho catalogue is not very accurate (e.g. the parallax listed is 9.1 ± 7.8 milliarcsec).

The analysis of our combined HARPS spectra, with a total *S/N* ratio above 500, provide $T_{\rm eff}$ = 5663 ± 20, $\log g$ = 3.84 ± 0.05, and [Fe/H] = −0.49 ± 0.02. These values were obtained following the methodology and line-lists used in Santos et al. (2004b). Similar values for the stellar parameters are obtained using the larger Fe I and Fe II line-list presented in Sousa et al. (2007), and the automatic ARES[2] code for line-equivalent width measurement ($T_{\rm eff}$ = 5693 ± 16, $\log g$ = 3.85 ± 0.05, and [Fe/H] = −0.48 ± 0.01). For the rest of this paper we consider the first set of parameters. The errors mentioned above denote internal errors only. Systematic errors affecting e.g. the temperature scale are thoroughly discussed in the literature (Santos et al. 2004b; Ramírez & Meléndez 2004; Casagrande et al. 2006; Masana et al. 2006), and no consensus seems to exist at this point. This discussion is, however, out of the scope of the current paper.

The effective temperature and surface gravity derived are compatible with the expected parameters of a slightly evolved solar-type star, being roughly compatible with the spectral type of G0 listed in the Simbad database. Using the method described in Pont & Eyer (2004) with the isochrones of Girardi et al. (2000) we derived a stellar mass and age of 0.99 ± 0.08 $M_\odot$ and 6−11 Gyr, respectively. The stellar radius inferred is 1.95 ± 0.26 $R_\odot$. The uncertainties in these parameters were derived using 2-sigma errors in the effective temperature, surface gravity and metallicity. Using this mass and radius together with the derived surface gravity and effective temperature, and making use of the bolometric correction of Flower (1996), we derive a distance of 90 pc to HD 171028, with an error around 15 pc if we consider a conservative error in the $\log g$ of 0.15 dex. No reddening corrections were taken into account in this estimate.

The values mentioned above are slightly different from those listed in the Nordström et al. (2004) catalogue ($T_{\rm eff}$ = 5432 K, [Fe/H] = −0.81 ± 0.02, Mass = 0.78 $M_\odot$, and distance of 43 pc). We note, however, that the photometric calibrations used by

---

[2] `http://www.astro.up.pt/~sousasag/ares`

Table 2. Chemical abundances for the several alpha and iron peak elements studied. For titanium, results based on both Ti I and Ti II lines are presented. The abundances given by Fe I and Fe II lines are the same (it is one of the conditions for the derivation of the stellar parameters – Santos et al. 2004b). The error in [X/H] represents the rms of the abundances given by the n(X) different lines used.

Element	$\log\epsilon_\odot$	[X/H]	n(X)	[X/Fe]
Fe	7.47	−0.49 ± 0.02	38	0.00
Si	7.55	−0.43 ± 0.02	11	0.06
Ca	6.36	−0.41 ± 0.05	13	0.08
Sc	3.10	−0.40 ± 0.05	6	0.09
Ti I	4.99	−0.44 ± 0.03	12	0.05
Ti II	4.99	−0.43 ± 0.04	4	0.06
V	4.00	−0.54 ± 0.04	8	−0.05
Cr	5.67	−0.56 ± 0.02	4	−0.07
Mn	5.39	−0.72 ± 0.06	4	−0.23
Co	4.92	−0.50 ± 0.03	6	−0.01
Ni	6.25	−0.53 ± 0.03	29	−0.04
Na	6.33	−0.42 ± 0.07	3	0.07
Mg	7.58	−0.44 ± 0.03	2	0.05
Al	6.47	−0.46 ± 0.01	2	0.03

Nordström et al. to derive these parameters (including the absolute magnitude used to derive the distance) are likely to only be valid for main-sequence stars.

From the HARPS spectra we derived a chromospheric activity index ($\log R'_{\rm HK} = -4.92$, with rms of 0.02) following a procedure similar to that presented in Santos et al. (2000). From the activity level and the $B - V$ colour we estimate a rotational period of 19 days (Noyes et al. 1984) and an age of 4 Gyr (Henry et al. 1996) (or at least above 2 Gyr – Pace & Pasquini 2004). These latter values are likely to be inaccurate due to the fact that HD 171028 is a metal-poor star and somewhat evolved off the main sequence (Wright 2004). The calibrations mentioned above were based on main-sequence stars, mostly of solar metallicity. In any case, the measured chromospheric activity level is compatible with HD 171028 being an old, chromospherically quiet star.

3.2.1. Abundances of different species

It is known that thick-disk stars have typically higher abundances of alpha elements (Bensby et al. 2003; Fuhrmann 2004). To try to indentify whether HD 171028 could be a member of this galactic population, we used the method and line-lists described in Gilli et al. (2006) and Santos et al. (2006) to derive the abundances of several alpha and iron-peak elements for HD 171028. The results, listed in Table 2, suggest that this star has typical abundances of thin disk solar-type stars (see also Gilli et al. 2006). In particular, no overabundance of alpha elements is seen when comparing with stars of similar [Fe/H].

No trace of the Li line at 6707.8 Å is found in our $S/N \sim 500$ spectrum of HD 171028. An upper limit of 0.6 mÅ was obtained for the Equivalent Width of the Li-line. This value translates into an upper limit of $\log\epsilon(Li) < 0.2$ dex. Such a value is compatible with its evolutionary status and effective temperature, although a large dispersion is seen in the Li abundances of sub-giant stars similar to HD 171028 (Randich et al. 1999; Lèbre et al. 1999).

Table 3. HARPS radial-velocity measurements of HD 171028.

JD	V_r [km s^{-1}]	$\sigma(V_r)$ [km s^{-1}]
2 453 310.4946	13.6319	0.0009
2 453 574.6582	13.5948	0.0008
2 453 575.6376	13.5924	0.0007
2 453 576.6401	13.5899	0.0008
2 453 577.6084	13.5939	0.0008
2 453 578.6591	13.5954	0.0007
2 453 669.5027	13.7099	0.0016
2 453 672.4942	13.7045	0.0013
2 453 862.8107	13.6268	0.0011
2 453 864.8024	13.6304	0.0011
2 453 870.7806	13.6268	0.0009
2 453 882.8334	13.6266	0.0010
2 453 883.8141	13.6219	0.0017
2 453 920.7281	13.6179	0.0008
2 454 166.9019	13.6329	0.0009
2 454 168.8885	13.6345	0.0008
2 454 172.8740	13.6417	0.0008
2 454 174.8916	13.6446	0.0008
2 454 196.8946	13.7075	0.0007

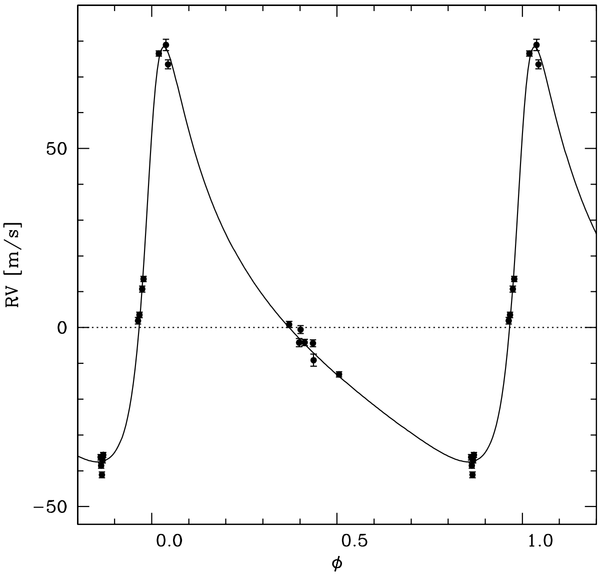

Fig. 2. *Top*: phase-folded radial-velocity measurements of HD 171028, and the best Keplerian fit to the data with a period of 538 days, eccentricity of 0.61, and semi-amplitude of 58 m s^{-1}.

3.3. HARPS orbital solution

As mentioned above, between October 2004 and April 2007 we obtained 19 accurate radial-velocity measurements of HD 171028 with the HARPS spectrograph. The complete radial velocity measurements obtained and the corresponding errors are presented in Table 3. It is worth noting that the errors quoted in the table, which are used to plot the error bars, refer solely to the instrumental (calibration) and photon-noise error share of the total error budget (e.g. activity and/or stellar oscillations are not considered, given the difficulty in obtaining a clear estimate of their influence).

Just after the first measurements were made the star was noted to be radial-velocity variable. A later analysis of the whole data set revealed the presence of a 538-day period radial-velocity signal. This signal is best fitted using a Keplerian fit with a semi-amplitude K of 58 m s^{-1}, and an eccentricity of 0.61 (Figs. 2 and 3). Given the mass for HD 171028, this corresponds to the

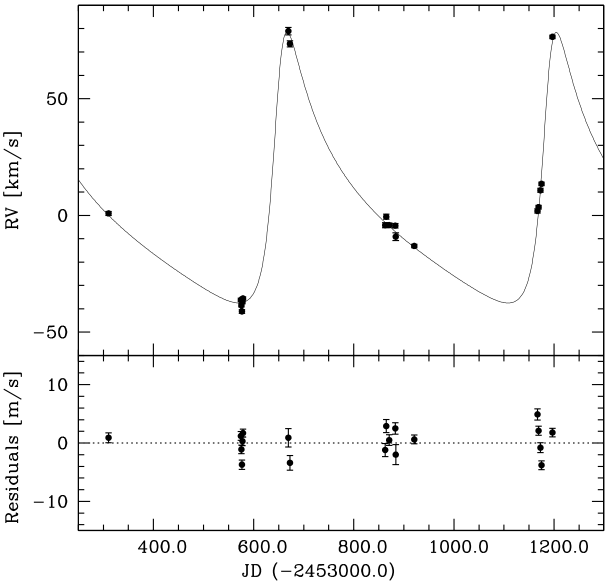

Fig. 3. *Top*: radial-velocity measurements of HD 171028 as a function of time, and the best Keplerian fit to the data. *Bottom*: residuals of the fit.

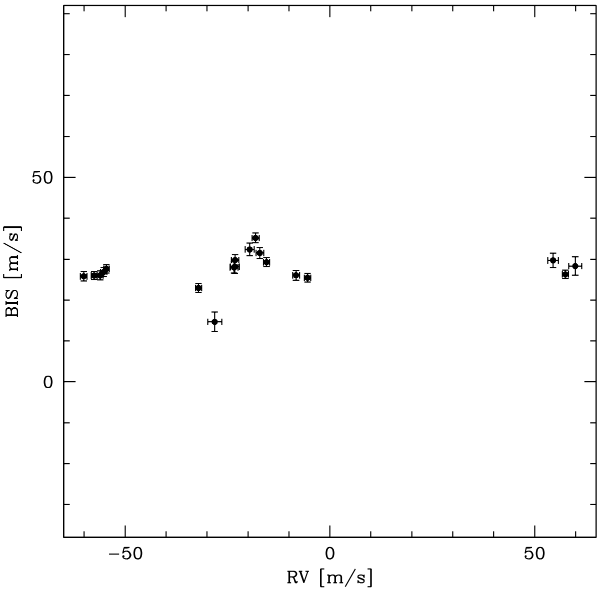

Fig. 4. BIS vs. radial-velocity for HD 171028. To evidence the nonexistence of a correlation, the vertical and horizontal scales are identical.

Table 4. Elements of the fitted orbit for HD 171028b.

P	538 ± 2	[d]
T	2453648.9205 ± 1.8584	[d]
a	1.29	[AU]
e	0.61 ± 0.01	
V_r	13.631 ± 0.001	[km s^{-1}]
ω	305 ± 1	[degr]
K_1	58.0 ± 0.4	[m s^{-1}]
$f_1(m)$	5.421×10^{-9}	[$M_\odot$]
$\sigma(O-C)$	2.4	[m s^{-1}]
N	19	
$m_2 \sin i$	1.83	[$M_{\rm Jup}$]

expected signal induced by the presence of a 1.83 Jupiter-masses (minimum-mass) companion (Table 4).

To understand if the periodic radial-velocity signal observed could have a non-planetary origin (Saar & Donahue 1997; Queloz et al. 2000; Santos et al. 2002), in Fig. 4 we plot the BIS of the CCF as a function of the radial-velocity. The result shows that no correlation exists between the two quantities, suggesting that stellar activity or stellar blends cannot explain the radial-velocity variation observed. Together with the low activity level of the star, we conclude that the 538-day orbital period observed can be better explained by the presence of a Jupiter-like planet orbiting HD 171028.

The residuals of the orbital fit have a rms of 2.4 m s^{-1}, slightly above the average photon-noise error of the measurements (0.95 m s^{-1}). The lower panel of the plot presented in Fig. 3 reveals some structure in the residuals after the 538-day period orbit is subtracted. Although we cannot exclude that this signal is due to the presence of another companion to the system, the fact that some structure is also present in the plot of Fig. 4 may hint at a non-planetary origin for the signal. More data are needed to settle this issue.

4. Concluding remarks

In this paper we present the detection of the first planet among the stars in the HARPS metal-poor planet search program, a giant planet with a minimum mass of 1.8 $M_{\rm Jup}$ orbiting HD 171028 in an eccentric trajectory every 538 days.

This detection adds to the small number of planets known to orbit stars with metallicity clearly below solar (e.g. Mayor et al. 2004; Cochran et al. 2007). While the correlation between the presence of planets and stellar metallicity is clearly established (Gonzalez et al. 2001; Santos et al. 2001, 2004b; Fischer & Valenti 2005), the detection of an increasing number of giant planets orbiting low-metallicity stars reopens the debate about the origin of these worlds. These findings show that giant planet formation is not completely inhibited around stars in the intermediate metal-poor regime.

These cases either represent the metal-poor tail of the giant planets formed by the core-accretion process, or they may hint at the existence of a different population of planets formed as a result of disk-instability processes. The precise study of the metallicity distribution of stars with planets suggests that there may be a "long" flat low-metallicity tail (Santos et al. 2004b; Udry & Santos 2007). Although statistics of metal-poor planet hosts is poorly developed, we can speculate that we may be observing a superposition of two populations. On the one hand, there are stars whose planets were formed by the metallicity dependent core-accretion process (Pollack et al. 1996; Ida & Lin 2004b), mostly populating the metal-rich regime. On the other hand, there is a less significant population of giant planets orbiting stars of all metallicities. The latter could have been formed by the disk-instability process (Boss 2002). We consider here that subsequent planet evolution processes (e.g. migration in the disk) are not strongly dependent on metallicity (Livio & Pringle 2003).

We should add, however, that according to the models, giant planets formed by the disk-instability process could have higher masses when compared with those formed by core-accretion (e.g. Matsuo et al. 2007). The lack of a clear correlation between planet-mass and stellar metallicity (e.g. Santos et al. 2003) may be an important caveat for the proposed scenario.

In this context it is interesting to see that HD 171028 is clearly one of the most metal-rich stars in the HARPS sample presented in this paper. Although statistically not relevant (note that our sample is clearly more populated at the metallicity range between −0.5 and −0.8), if confirmed this fact could lend support to the core-accretion model.

Also interesting is the fact that HD 171028 is slightly evolved off the main-sequence. In a very recent study, Pasquini et al. (2007) present evidence that giant stars with planets are likely to be not as metal-rich as their dwarf counterparts (see also da Silva et al. 2006a). Although other explanations exist (e.g. the higher mass of the stars, and eventually of the proto-planetary disks, may significantly change the planet formation efficiency – Laughlin et al. 2004; Endl et al. 2006; Bonfils et al. 2007; Johnson et al. 2007), this interesting conclusion could suggest that planetary pollution may be more important than previously thought (Pinsonneault et al. 2001; Santos et al. 2003, 2004b; Fischer & Valenti 2005). We note, however, that no clear connection seems to be present between the stellar evolution status and [Fe/H] among dwarfs and sub-giant stars with planets (Santos et al. 2003; Fischer & Valenti 2005). In the sub-giant branch, planet-host stars are still metal-rich when compared with "single" field stars, even though major dilution processes may have occurred. The tables of Santos et al. (2004b, 2005) and Sousa et al. (2006), also show that low metallicity among planet hosts is not restricted to evolved stars. Such observations could be expected if stellar pollution was a frequent outcome of the planet formation process. Out of 14 stars with metallicity below −0.20 dex, only 5 are likely to be evolved ($\log g < 4.2$), while 7 "definite" dwarf stars ($\log g > 4.4$) are also metal-poor. On the other hand, several evolved stars exist with metallicity well above solar. Finally, although some caveats have been discussed (Vauclair 2004), the lack of any correlation between stellar metallicity and convective envelope mass is still an important argument against pollution being the main mechanism responsible for the observed metal-rich nature of planet-host stars (Pinsonneault et al. 2001; Santos et al. 2003; Fischer & Valenti 2005). The K-dwarf stars with planets, with deep convective regions, would require an excessive infall of planetary material to be enriched to the observed level.

The continuation of the program presented here will certainly provide important constraints for this discussion. On the one hand, it will help to understand what is the lower stellar metallicity limit at which giant planets are still able to form (see discussion in Matsuo et al. 2007). On the other hand, with the adequate observing strattegy, it will allow access to the frequency of Neptune-mass planets orbiting lower metallicity stars (Udry et al. 2006). Although the (unknown) disk masses may also have a crucial influence on the planet formation efficiency, such results would clearly have important implications for the models of planet formation and evolution.

Acknowledgements. We would like to thank F. Pont for help in deriving the stellar mass, age and radius, as well as to our referee L. Pasquini, who helped to improve the clarity of the paper. This work made use of the Simbad database. NCS would like to thank the support from Fundação para a Ciência e a Tecnologia, Portugal, in the form of a grant (reference POCI/CTE-AST/56453/2004). This work was supported in part by the EC's FP6 and by FCT (with POCI2010 and FEDER funds), within the HELAS international collaboration.

References

Bensby, T., Feltzing, S., & Lundström, I. 2003, A&A, 410, 527
Benz, W., Mordasini, C., Alibert, Y., & Naef, D. 2006, in Tenth Anniversary of 51 Peg-b: Status of and prospects for hot Jupiter studies, ed. L. Arnold, F. Bouchy, & C. Moutou, 24
Bonfils, X., Forveille, T., Delfosse, X., et al. 2005, A&A, 443, L15
Bonfils, X., Mayor, M., Delfosse, X., et al. 2007, ArXiv e-prints, 704
Boss, A. P. 1997, Science, 276, 1836
Boss, A. P. 2002, ApJ, 567, L149
Bouchy, F., Bazot, M., Santos, N. C., Vauclair, S., & Sosnowska, D. 2005a, A&A, 440, 609
Bouchy, F., Udry, S., Mayor, M., et al. 2005b, A&A, 444, L15
Casagrande, L., Portinari, L., & Flynn, C. 2006, MNRAS, 373, 13
Cochran, D. C., Endl, M., Wittenmyer, R. A., & Bean, J. L. 2007, ApJ, in press
da Silva, L., Girardi, L., Pasquini, L., et al. 2006a, A&A, 458, 609
da Silva, R., Udry, S., Bouchy, F., et al. 2006b, A&A, 446, 717
Endl, M., Cochran, W. D., Kürster, M., et al. 2006, ApJ, 649, 436
ESA 1997, The Hipparcos and Tycho Catalogues
Fischer, D. A., & Valenti, J. 2005, ApJ, 622, 1102
Fischer, D. A., Laughlin, G., Butler, P., et al. 2005, ApJ, 620, 481
Flower, P. J. 1996, ApJ, 469, 355
Fuhrmann, K. 2004, Astron. Nachr., 325, 3
Gilli, G., Israelian, G., Ecuvillon, A., Santos, N. C., & Mayor, M. 2006, A&A, 449, 723
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
Gonzalez, G. 1997, MNRAS, 285, 403
Gonzalez, G., Laws, C., Tyagi, S., & Reddy, B. E. 2001, AJ, 121, 432
Henry, T. J., Soderblom, D. R., Donahue, R. A., & Baliunas, S. L. 1996, AJ, 111, 439
Ida, S., & Lin, D. N. C. 2004a, ApJ, 604, 388
Ida, S., & Lin, D. N. C. 2004b, ApJ, 616, 567
Johnson, J. A., Butler, R. P., Marcy, G. W., et al. 2007, ArXiv e-prints, 707
Laughlin, G., Bodenheimer, P., & Adams, F. C. 2004, ApJ, 612, L73
Lèbre, A., de Laverny, P., de Medeiros, J. R., Charbonnel, C., & da Silva, L. 1999, A&A, 345, 936
Livio, M., & Pringle, J. E. 2003, MNRAS, 346, L42
Lovis, C., Mayor, M., Bouchy, F., et al. 2005, A&A, 437, 1121
Lovis, C., Mayor, M., Pepe, F., et al. 2006, Nature, 441, 305
Masana, E., Jordi, C., & Ribas, I. 2006, A&A, 450, 735
Matsuo, T., Shibai, H., Ootsubo, T., & Tamura, M. 2007, ArXiv Astrophysics e-prints
Mayer, L., Quinn, T., Wadsley, J., & Stadel, J. 2002, Science, 298, 1756
Mayor, M., Pepe, F., Queloz, D., et al. 2003, The Messenger, 114, 20
Mayor, M., Udry, S., Naef, D., et al. 2004, A&A, 415, 391
Melo, C., Santos, N. C., Gieren, W., et al. 2007, A&A, 467, 721
Mizuno, H. 1980, Progr. Theor. Phys., 64, 544
Nordström, B., Mayor, M., Andersen, J., et al. 2004, A&A, 418, 989
Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763
Olsen, E. H. 1994, A&AS, 106, 257
Pace, G., & Pasquini, L. 2004, A&A, 426, 1021
Pasquini, L., Doellinger, M. P., Weiss, A., et al. 2007, ArXiv e-prints, 707
Pepe, F., Mayor, M., Queloz, D., et al. 2004, A&A, 423, 385
Pinsonneault, M. H., DePoy, D. L., & Coffee, M. 2001, ApJ, 556, L59
Pollack, J., Hubickyj, O., Bodenheimer, P., et al. 1996, Icarus, 124, 62
Pont, F., & Eyer, L. 2004, MNRAS, 351, 487
Queloz, D., Mayor, M., Weber, L., et al. 2000, A&A, 354, 99
Ramírez, I., & Meléndez, J. 2004, ApJ, 609, 417
Randich, S., Gratton, R., Pallavicini, R., Pasquini, L., & Carretta, E. 1999, A&A, 348, 487
Reid, I. N. 2002, PASP, 114, 306
Saar, S. H., & Donahue, R. A. 1997, ApJ, 485, 319
Santos, N. C., Mayor, M., Naef, D., et al. 2000, A&A, 361, 265
Santos, N. C., Israelian, G., & Mayor, M. 2001, A&A, 373, 1019
Santos, N. C., Mayor, M., Naef, D., et al. 2002, A&A, 392, 215
Santos, N. C., Israelian, G., Mayor, M., Rebolo, R., & Udry, S. 2003, A&A, 398, 363
Santos, N. C., Bouchy, F., Mayor, M., et al. 2004a, A&A, 426, L19
Santos, N. C., Israelian, G., & Mayor, M. 2004b, A&A, 415, 1153
Santos, N. C., Israelian, G., Mayor, M., et al. 2005, A&A, 437, 1127
Santos, N. C., Ecuvillon, A., Israelian, G., et al. 2006, A&A, 458, 997
Sato, B., Fischer, D. A., Henry, G. W., et al. 2005, ApJ, 633, 465
Setiawan, J., Hatzes, A. P., von der Lühe, O., et al. 2003, A&A, 398, L19
Sousa, S. G., Santos, N. C., Israelian, G., Mayor, M., & Monteiro, M. J. P. F. G. 2006, A&A, 458, 873
Sousa, S. G., Santos, N. C., Israelian, G., Mayor, M., & Monteiro, M. J. P. F. G. 2007, A&A, 469, 783
Sozzetti, A., Torres, G., Latham, D. W., et al. 2006, ApJ, 649, 428
Tinney, C. G., Butler, R. P., Marcy, G. W., et al. 2002, ApJ, 571, 528
Udry, S., & Santos, N. 2007, ARA&A, 45, 397
Udry, S., Mayor, M., Benz, W., et al. 2006, A&A, 447, 361
Udry, S., Bonfils, X., Delfosse, X., et al. 2007, A&A, 469, L43
Vauclair, S. 2004, ApJ, 605, 874
Wright, J. T. 2004, AJ, 128, 1273