A&A 398, 363–376 (2003)
DOI: 10.1051/0004-6361:20021637


Astronomy & Astrophysics

# Statistical properties of exoplanets⋆

## II. Metallicity, orbital parameters, and space velocities

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Received 19 September 2002 / Accepted 7 November 2002

**Abstract.** In this article we present a detailed spectroscopic analysis of more than 50 extra-solar planet host stars. Stellar atmospheric parameters and metallicities are derived using high resolution and high S/N spectra. The spectroscopy results, added to the previous studies, imply that we have access to a large and uniform sample of metallicities for about 80 planet hosts stars. We make use of this sample to confirm the metal-rich nature of stars with planets, and to show that the planetary frequency is rising as a function of the [Fe/H]. Furthermore, the source of this high metallicity is shown to have most probably a "primordial" source, confirming previous results. The comparison of the orbital properties (period and eccentricity) and minimum masses of the planets with the stellar properties also reveal some emerging but still not significant trends. These are discussed and some explanations are proposed. Finally, we show that the planet host stars included in the CORALIE survey have similar kinematical properties as the whole CORALIE volume-limited planet search sample. Planet hosts simply seem to occupy the metal-rich envelope of this latter population.

**Key words.** stars: abundances – stars: fundamental parameters – stars: chemically peculiar – stars: evolution – planetary systems – solar neighborhood

## 1. Introduction

The discovery of now more than 100 extra-solar giant planets[1] opened a wide range of questions regarding the understanding of the mechanisms of planetary formation. To find a solution for the many problems risen, we need observational constraints. These can come, for example, from the analysis of orbital parameters of the known planets, like the distribution of planetary masses (Jorissen et al. 2001; Zucker & Mazeh 2001; Udry et al. 2001), eccentricities, or orbital periods (for a review see e.g. Udry et al. 2001; Mayor & Santos 2002). In fact, as new and longer period planets are found, more interesting correlations are popping up. Examples of these are the discovery that there is a paucity of high mass companions orbiting in short period orbits (Zucker & Mazeh 2002; Udry et al. 2002a), or the interesting lack of long-period low-mass planets (Udry et al. 2002b).

But further evidences are coming from the study of the planet host stars themselves. Precise spectroscopic studies have revealed that stars with planets seem to be particularly metal-rich when compared with "single" field dwarfs (Gonzalez 1997; Fuhrmann et al. 1997; Gonzalez 1998; Santos et al. 2000; Gonzalez et al. 2001; Santos et al. 2001a,b). Furthermore, the frequency of planets seems to be a strong function of [Fe/H] (Santos et al. 2001a, hereafter Paper II). These facts, that were shown not to result from any sampling bias (Paper II), are most probably telling us that the metallicity plays a key role in the formation of a giant planet, or at least of a giant planet like the ones we are finding now.

The source of this metallicity "excess" has, however, been a matter of debate. Some authors have suggested that the high metal content of the planet host stars may have an external origin: it results from the addition of metal-rich (hydrogen poor) material into the convective envelope of the star, a process that could result from the planetary formation process itself (Gonzalez 1998; Laughlin 2000; Gonzalez et al. 2001;

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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 ESO telescope, 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. tables at http://obswww.unige.ch/exoplanets/

Smith et al. 2001; Murray & Chaboyer 2002). Evidences for the infall of planetary material have in fact been found for a few planet host stars (e.g. Israelian et al. 2001; Laws & Gonzalez 2001; Israelian et al. 2002), although not necessarily able to change considerably the overall metal content (see e.g. Sandquist et al. 2002). In fact, most evidences today suggest that the metallicity "excess" as a whole has a "primordial" origin (Pinsonneault et al. 2001; Santos et al. 2001a,b, 2002b; Sadakane et al. 2002), and thus that the metal content of the cloud giving birth to the star and planetary system is indeed a key parameter to form a giant planet.

Besides the simple correlation between the presence of a planet and the high metal-content of its host star, there are some hints that the metallicity might be correlated with the planetary orbital properties. For example, Gonzalez (1998) and Queloz et al. (2000) have shown some evidences that stars with very short-period planets (i.e. small semi-major axes) may be particularly metal-rich, even amongst the planetary hosts. More recent studies have, however, failed to confirm this relation (Paper II).

With the number of new planets growing every day, it is extremely important to survey the samples for new emerging correlations between the stellar properties and the characteristics (minimum masses and orbital parameters) of the planetary companions. In this paper we focus exactly on this point. We have obtained high-resolution and high-$S/N$ spectra of more than 50 extra-solar planet host stars, most of them without any previous detailed spectroscopic analysis. These new determinations bring to about 80 our sample of planet host stars with homogeneous derived spectroscopic parameters. The structure of this article goes as follows. In Sect. 2 we describe the observations and the chemical analysis. In Sect. 3 we review the current status of the metallicity distribution of stars with planets, further discussing its origin, and in Sect. 4 we analyze the relation between the orbital parameters and the metallicity. In Sect. 5 we finally analyze the space velocities of planet and non-planet host stars, comparing them with the stellar metallicity. We conclude in Sect. 6.

## 2. Observations and spectroscopic analysis

### 2.1. Observations and data reduction

High resolution spectra for more than 50 planet hosts stars were obtained during several runs using 6 different spectrographs. The general characteristics of these instruments are presented in Table 1.

The spectra have in general a $S/N$ ratio between 150 and 400, but are as high as 1000 for the UVES spectra. Except for the UES spectra, all the others cover very well all the spectral domain without any significant gaps, permitting us to measure the Equivalent Widths for most of the spectral lines used (see Santos et al. (2000) – hereafter Paper I – and Paper II). But even in this case, the gaps did not imply any strong limitations, since the available lines still have a wide variety of equivalent widths and lower excitation potentials, essential to the precise determination of the stellar parameters (see next section).

**Table 1.** Spectrographs used for the current study and their spectral coverage and resolution.

| Spectrograph/Telescope | Resolution ($\lambda/\Delta\lambda$) | Coverage (Å) |
|---|---|---|
| CORALIE/1.2-m Euler Swiss | 50 000 | 3 800–6 800 |
| FEROS/1.52-m ESO | 48 000 | 3 600–9 200 |
| UES/4-m William Hershel | 55 000 | 4 600–7 800 |
| SARG/3.5-m TNG | 57 000 | 5 100–10 100 |
| UVES/VLT 8-m Kueyen UT2 | 110 000 | 4 800–6 800 |
| ELODIE/1.93-m OHP | 48 000 | 3 800–6 800 |

Data reduction was done using IRAF[2] tools in the `echelle` package. Standard background correction, flat-field, and extraction procedures were used. In all the cases, the wavelength calibration was done using a ThAr lamp spectrum taken during the same night.

We have compared the Equivalent Widths ($EW$) for some stars for which we have obtained spectra using different instruments to check for possible systematics. In all cases, the average difference of the $EW$s is within 1–2 mÅ, and usually lower than 1 mÅ. As can be also verified from Table 2 of this article and Table 2 from Paper II, these possible small systematics do not seem to affect significantly the analysis of the atmospheric parameters and metallicity. The only star that has large variations in the derived atmospheric parameters is HD 19994. This variation might be connected with the fact that this late F dwarf has a high rotational velocity $v \sin i = 8.1$ km s$^{-1}$ (from the calibration of the CORALIE Cross-Correlation Function presented in Santos et al. 2002a), a sign of relative youth and (most probably) activity related phenomena.

### 2.2. Stellar parameters and chemical analysis

In this paper we use the same technique, line-lists, and model atmospheres as in Papers I and II. The abundance analysis was done in standard Local Thermodynamic Equilibrium (LTE) using a revised version of the code MOOG (Sneden 1973), and a grid of Kurucz (1993) ATLAS9 atmospheres.

The atmospheric parameters were obtained from the Fe I and Fe II lines by iterating until the correlation coefficients between $\log \epsilon$(Fe I) and $\chi_l$, 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. This procedure gives very good results since the set of Fe I lines has a very wide range of excitation potentials.

The results of our analysis are presented in Table 2. The number of measured Fe I and Fe II lines is always between 24 and 39, and 4 and 8, respectively. The rms around the mean individual abundances given by the lines has values between 0.03 and 0.07 dex in most cases. The errors in $T_{\rm eff}$, $\log g$, $\xi_t$ and [Fe/H] were computed as in Gonzalez & Vanture (1998). For a typical measure the uncertainties are usually lower than 50 K, 0.15 dex, 0.10 km s$^{-1}$, and 0.06 dex, respectively

[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.

**Table 2.** Stellar parameters derived in the current study. $\xi_t$ denotes the microturbulence parameters. For a list of the planet discovery papers see tables at `http://obswww.unige.ch/exoplanets/` and `http://cfa-www.harvard.edu/planets/`. A more complete table with the number of Fe I and Fe II lines used and the dispersions will be available at the 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/398/363`

| Star | $T_{\rm eff}$ (K) | $\log g$ (cgs) | $\xi_t$ (km s$^{-1}$) | [Fe/H] | Inst. ($^a$) | $M_\star^{\dagger\dagger\dagger}$ ($M_\odot$) | Star | $T_{\rm eff}$ (K) | $\log g$ (cgs) | $\xi_t$ (km s$^{-1}$) | [Fe/H] | Inst. ($^a$) | $M_\star^{\dagger\dagger\dagger}$ ($M_\odot$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HD 142 | 6290 | 4.38 | 1.91 | 0.11 | [2] | 1.26 | HD 117176 | 5530 | 4.05 | 1.08 | −0.05 | [4] | 0.92 |
| HD 2039 | 5990 | 4.56 | 1.24 | 0.34 | [1] | 1.20 | HD 128311 | 4950 | 4.80 | 1.00 | 0.10 | [3] | 0.76 |
| HD 4203 | 5650 | 4.38 | 1.15 | 0.40 | [2] | 0.93 | HD 130322 | 5430 | 4.62 | 0.92 | 0.06 | [4] | 1.04 |
| HD 4208 | 5625 | 4.54 | 0.95 | −0.23 | [2] | 0.86 | HD 134987 | 5780 | 4.45 | 1.06 | 0.32 | [4] | 1.05 |
| HD 8574 | 6080 | 4.41 | 1.25 | 0.05 | [4] | 1.17 | HD 136118 | 6175 | 4.18 | 1.61 | −0.06 | [4] | 1.28 |
| HD 9826 | 6120 | 4.07 | 1.50 | 0.10 | [4] | 1.29 | HD 137759 | 4750 | 3.15 | 1.78 | 0.09 | [4] | – |
| HD 10697 | 5665 | 4.18 | 1.19 | 0.14 | [4] | 1.22 | HD 141937 | 5925 | 4.62 | 1.16 | 0.11 | [3]†† | 1.10 |
| HD 12661 | 5715 | 4.49 | 1.09 | 0.36 | [3] | 1.05 | HD 143761 | 5835 | 4.40 | 1.29 | −0.21 | [4] | 0.95 |
| HD 19994 | 6165 | 4.13 | 1.49 | 0.23 | [1]† | 1.34 | HD 145675 | 5255 | 4.40 | 0.68 | 0.51 | [4] | 0.90 |
| | 6250 | 4.27 | 1.56 | 0.30 | [2]† | 1.35 | HD 147513 | 5880 | 4.58 | 1.17 | 0.07 | [1] | 1.11 |
| | 6105 | 4.02 | 1.51 | 0.18 | [5] | 1.34 | HD 150706 | 6000 | 4.62 | 1.16 | 0.01 | [3] | 1.21 |
| (average) | 6175 | 4.14 | 1.52 | 0.21 | | 1.34 | HD 160691 | 5820 | 4.44 | 1.23 | 0.33 | [1]†† | 1.10 |
| HD 20367 | 6100 | 4.55 | 1.31 | 0.14 | [6] | 1.17 | HD 168443 | 5600 | 4.30 | 1.18 | 0.06 | [4] | 0.96 |
| HD 23079 | 5945 | 4.44 | 1.21 | −0.11 | [2] | 1.00 | HD 177830 | 4840 | 3.60 | 1.18 | 0.32 | [4] | 1.03 |
| HD 23596 | 6125 | 4.29 | 1.32 | 0.32 | [3] | 1.30 | HD 179949 | 6235 | 4.41 | 1.38 | 0.21 | [1]†† | 1.25 |
| HD 27442 | 4890 | 3.89 | 1.24 | 0.42 | [2] | 0.83 | HD 186427 | 5765 | 4.46 | 1.03 | 0.09 | [4] | 0.99 |
| HD 30177 | 5590 | 4.45 | 1.07 | 0.39 | [1] | 1.00 | HD 187123 | 5855 | 4.48 | 1.10 | 0.14 | [4] | 1.05 |
| HD 33636 | 5990 | 4.68 | 1.22 | −0.05 | [2] | 1.12 | HD 190228 | 5360 | 4.02 | 1.12 | −0.24 | [3]† | 0.84 |
| HD 37124 | 5565 | 4.62 | 0.90 | −0.37 | [3] | 0.76 | | 5325 | 3.95 | 1.10 | −0.23 | [4] | 0.82 |
| HD 39091 | 5995 | 4.48 | 1.30 | 0.09 | [1]† | 1.10 | (average) | 5340 | 3.99 | 1.11 | −0.24 | | 0.83 |
| HD 46375 | 5315 | 4.54 | 1.11 | 0.21 | [3] | 0.83 | HD 190360 | 5590 | 4.48 | 1.06 | 0.25 | [3] | 0.96 |
| HD 50554 | 6050 | 4.59 | 1.19 | 0.02 | [3] | 1.11 | HD 192263⋆ | 4995 | 4.76 | 0.90 | 0.04 | [2] | 0.75 |
| HD 74156 | 6105 | 4.40 | 1.36 | 0.15 | [2] | 1.27 | HD 195019 | 5845 | 4.39 | 1.23 | 0.08 | [4] | 1.06 |
| HD 75732A | 5307 | 4.58 | 1.06 | 0.35 | [3] | 0.88 | | 5832 | 4.34 | 1.24 | 0.09 | [1]†† | 1.05 |
| HD 80606 | 5570 | 4.56 | 1.11 | 0.34 | [3] | 1.03 | (average) | 5840 | 4.36 | 1.24 | 0.08 | | 1.06 |
| HD 82943 | 6025 | 4.54 | 1.10 | 0.33 | [1]† | 1.15 | HD 196050 | 5905 | 4.41 | 1.40 | 0.21 | [1] | 1.10 |
| | 6025 | 4.53 | 1.15 | 0.30 | [5] | 1.15 | HD 209458 | 6120 | 4.56 | 1.37 | 0.02 | [5] | 1.15 |
| (average) | 6025 | 4.54 | 1.12 | 0.32 | | 1.15 | HD 210277 | 5575 | 4.44 | 1.12 | 0.23 | [2]† | 0.94 |
| HD 92788 | 5820 | 4.60 | 1.12 | 0.34 | [1] | 1.10 | | 5560 | 4.46 | 1.03 | 0.21 | [4] | 0.93 |
| HD 95128 | 5925 | 4.45 | 1.24 | 0.05 | [4] | 1.05 | (average) | 5570 | 4.45 | 1.08 | 0.22 | | 0.94 |
| HD 106252 | 5890 | 4.40 | 1.06 | −0.01 | [1]†† | 1.02 | HD 213240 | 5975 | 4.32 | 1.30 | 0.16 | [1] | 1.22 |
| HD 108874 | 5615 | 4.58 | 0.93 | 0.25 | [3] | 0.96 | HD 216435 | 5905 | 4.16 | 1.26 | 0.22 | [1] | 1.26 |
| HD 114386 | 4875 | 4.69 | 0.63 | 0.00 | [1] | 0.68 | HD 216437 | 5875 | 4.38 | 1.30 | 0.25 | [1] | 1.06 |
| HD 114729 | 5820 | 4.20 | 1.03 | −0.26 | [3] | 0.94 | HD 217014 | 5805 | 4.51 | 1.22 | 0.21 | [2] | 1.04 |
| HD 114762 | 5870 | 4.25 | 1.28 | −0.72 | [5] | 0.80 | HD 222582 | 5850 | 4.58 | 1.06 | 0.06 | [3] | 1.02 |
| HD 114783 | 5160 | 4.75 | 0.79 | 0.16 | [4] | 0.88 | | | | | | | |

[a] The instruments are [1] CORALIE, [2] FEROS, [3] UES, [4] SARG, [5] UVES, and [6] ELODIE.
† Already published in Santos et al. (2001a) (Paper II).
†† Already published in Santos et al. (2001b).
††† From the isochrones of Schaller et al. (1992), Schaerer et al. (1993) and Schaerer et al. (1992).
⋆ The existence of a planet around HD192263 was recently put in cause by Henry et al. (2002); we think, however, that these authors have not shown enough evidences against the presence of a planet, and thus we prefer to keep this star in the planet-hosts sample (Santos et al., in preparation).

(see Paper II)[3]. The only important exceptions are the cases of HD 20367 (for which the lower quality ELODIE spectra with $S/N \sim 80$–100 were responsible for errors of the order of 100 K, 0.20 dex, 0.15 km s$^{-1}$, and 0.10 dex in $T_{\rm eff}$, $\log g$, $\xi_t$ and [Fe/H], respectively) and for HD 137759, a giant star for which the dispersion in the [Fe/H] values for individual lines was quite high[4]. The masses were then determined from the theoretical isochrones of Schaller et al. (1992), Schaerer et al. (1993) and Schaerer et al. (1992), using $M_V$ computed from

[3] These represent relative errors, and not absolute ones.

[4] In this case the estimated errors in $T_{\rm eff}$, $\log g$, $\xi_t$ and [Fe/H] are of 150 K, 0.40 dex, 0.15 km s$^{-1}$, and 0.17 dex, respectively.

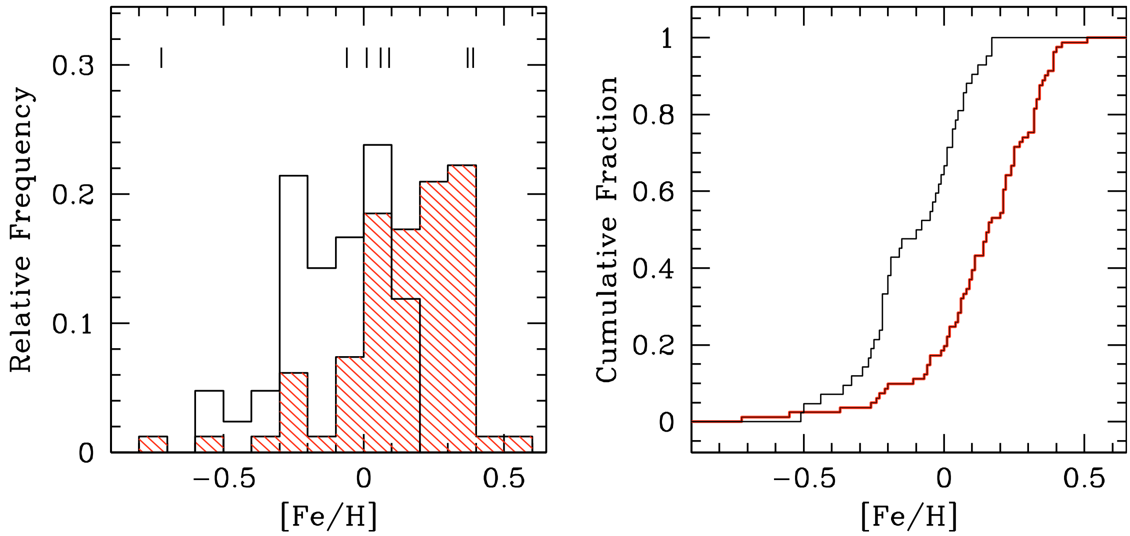


**Fig. 1.** *Left*: metallicity distribution for stars with planets (hashed histogram) compared with the same distribution for the field dwarfs presented in Paper II (empty histogram). The vertical lines represent stars with brown dwarf candidate companions. *Right*: the cumulative functions of both samples. A Kolmogorov-Smirnov test shows the probability for the two populations being part of the same sample is around $10^{-7}$.

Hipparcos parallaxes (ESA 1997) and $T_{\rm eff}$ obtained from spectroscopy. We adopt a typical error of 0.1 $M_\odot$ for the masses.

## 3. Confirming the excess metallicity

In Fig. 1 we plot the metallicity distribution for all the stars known to have companions with minimum masses lower than ~18 $M_{\rm Jup}$ (hashed histogram) when compared to the same distribution for a volume limited sample of stars with no (known) planetary companions (open histogram) – see Paper II.

For the planet host stars, most of the metallicity values ([Fe/H]) were taken from Table 2[5] and from Table 2 of Paper II. HD 39091, a star that was included in the "single" star comparison sample in Paper II, was recently discovered to harbor a brown dwarf companion (Jones et al. 2002). This star was thus taken out from this latter sample, and included in the planet sample. For 4 other stars for which we could not obtain spectra, values that were computed using the same technique (and are thus compatible with ours) are available. These are for BD −10 3166 (Gonzalez et al. 2001), HD 89744 (Gonzalez et al. 2001), HD 120136 (Gonzalez & Laws 2000), and HD 178911 B (Zucker et al. 2002b). The parameters ($T_{\rm eff}$, $\log g$, $\xi_t$, [Fe/H]) listed by these authors are (5320, 4.38, 0.85, 0.33), (6338, 4.17, 1.55, 0.30), (6420, 4.18, 1.25, 0.32), and (5650, 4.65, 0.85, 0.28), respectively.

We note that from the 89 stars known to harbor low mass (planetary or brown dwarf) companions, only 7 lack a metallicity determination[6].

It is important to remember that the metallicity for the two samples of stars plotted in Fig. 1 was derived using exactly the same method, and are thus both in the same scale (Paper II). This plot thus clearly confirms the already known trend that stars with planetary companions are more metal-rich (in average) that field dwarfs. The average metallicity difference between the two samples is about 0.24 dex, and the probability that the two distributions belong to the same sample is of the order of $10^{-7}$.

In Fig. 1, stars having "planetary" companions with masses higher than 10 $M_{\rm Jup}$ are denoted by the vertical lines. Given the still low number, it is impossible to do any statistical study of this group. It is interesting though to mention that two of the stars having companions in this mass regime (HD 202206 and HD 38529) have very high metallicities ([Fe/H] = 0.39 and 0.37, respectively), while one other (HD 114762) has the lowest metallicity of all the objects in the sample ([Fe/H] = −0.72). This large dispersion might be seen as an evidence that (at least part of) the higher mass objects were formed by the same physical mechanisms as their lower mass counterparts; the 13 $M_{\rm Jup}$ deuterium burning limit has no role in this matter. Furthermore, this represents a good example to show that the metallicity by itself cannot be used as a planetary identification argument, contrarily to what has been used by Chen & Zhao (2001).

We have tried to see if there were any differences between those stars having multiple planetary systems and stars having one single planet. The analysis revealed no significant trend. This negative result is probably not only due to the low number of points used, but most of all to the fact that as can be seen in the literature (e.g. Fischer et al. 2001), many planet host stars do present long term trends, some of them that might be induced by other planetary companions.

### *3.1. The probability of planet formation*

More interesting conclusions can be taken by looking at the shape of the distribution of stars with planets. As it as been discussed in Paper II, this distribution is rising with [Fe/H], up to a value of ~0.4, after which we see a sharp cutoff. This cutoff

[5] The only star not used was HD137759 (a K giant); we prefer to keep it out in the rest of the analysis.

[6] These are: GJ 876 (an M dwarf), HD 40979, HD 49674, HD 68988, HD 72659, HD 73526, and HD 76700.

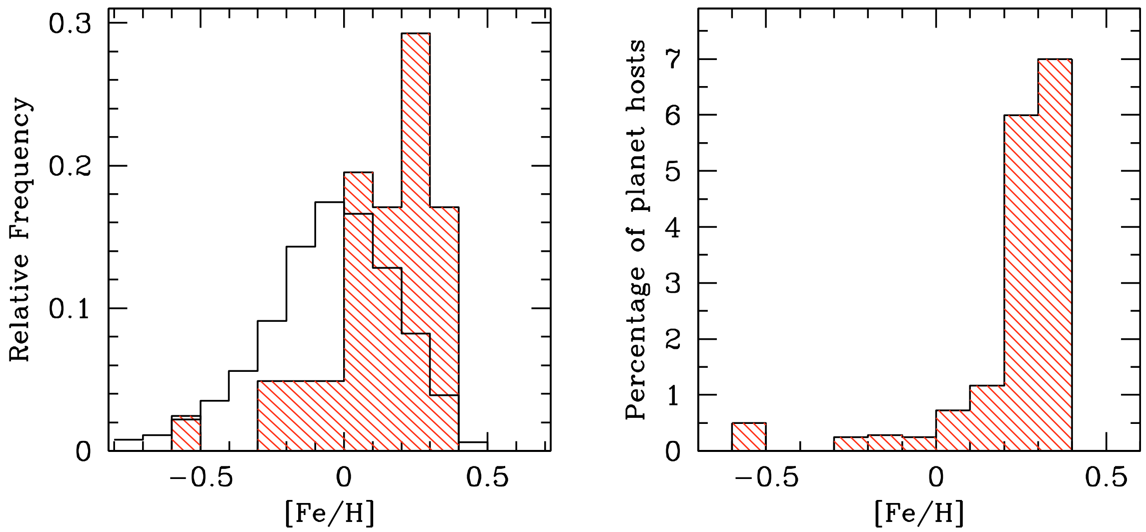


**Fig. 2.** *Left*: metallicity distribution of stars with planets making part of the CORALIE planet search sample (shaded histogram) compared with the same distribution for the about 1000 non binary stars in the CORALIE volume-limited sample (see text for more details). *Right*: the percentage of stars belonging to the CORALIE search sample that have been discovered to harbor planetary mass companions plotted as a function of the metallicity. The vertical axis represents the percentage of planet hosts with respect to the total CORALIE sample.

suggests that we may be looking at the approximate limit on the metallicity of the stars in the solar neighborhood.

Here we have repeated the analysis presented in Paper II, but using only the planet host stars included in the well defined CORALIE sample[7]. This sub-sample has a total of 41 objects, ∼60% of them having planets discovered in the context of the CORALIE survey itself. Here we have included all stars known to have companions with minimum masses lower than ∼18 $M_{\rm Jup}$; changing this limit to e.g. 10 $M_{\rm Jup}$ does not change any of the results presented below.

The fact that planets seem to orbit the most metal-rich stars in the solar neighborhood has led some groups to build planet search samples based on the high metal content of their host stars. Examples of these are the stars BD-10 3166 (Butler et al. 2000), HD 4203 (Vogt et al. 2002), and HD 73526, HD 76700, HD 30177, and HD 2039 (Tinney et al. 2002). Although clearly increasing the planet detection rate, these kind of metallicity biased samples completely spoil any statistical study. Using only stars being surveyed for planets in the context of the CORALIE survey (none of these 6 stars is included), a survey that has never used the metallicity as a favoring quantity for looking for planets, has thus the advantage of minimizing this bias.

As we can see from Fig. 2 (left panel), the metallicity distribution for the planet host stars included in the CORALIE sample does show an increasing trend with [Fe/H]. In the figure, the empty histogram represents the [Fe/H] distribution for a large volume limited sample of stars included in the CORALIE survey (Udry et al. 2000). The metallicities for this latter sample were computed from a precise calibration of the CORALIE Cross-Correlation Function (see Santos et al. 2002a); since the calibrators used were the stars presented in Paper I, Paper II, and this paper, the final results are in the very same scale.

The knowledge of the metallicity distribution for stars in the solar neighborhood (and included in the CORALIE sample) permits us to determine the percentage of planet host stars per metallicity bin. The result is seen in Fig. 2 (right panel). As we can perfectly see, the probability of finding a planet host is a strong function of its metallicity. This result confirms former analysis done in Paper II and by Reid (2002). For example, here we can see that about 7% of the stars in the CORALIE sample having metallicity between 0.3 and 0.4 dex have been discovered to harbor a planet. On the other hand, less than 1% of the stars having solar metallicity seem to have a planet. This result is thus probably telling us that the probability of forming a giant planet, or at least a planet of the kind we are finding now, depends strongly on the metallicity of the gas that gave origin to the star and planetary system. This might be simple explained if we consider that the higher the metallicity (i.e. dust density of the disk) the higher might be the probability of forming a core (and an higher mass core) before the disk dissipates (Pollack et al. 1996; Kokubo & Ida 2002).

Although it is unwise to draw any strong conclusions based on only one point, it is worth noticing that our own Sun is in the "metal-poor" tail of the planet host [Fe/H] distribution. Other stars having very long period systems (more similar to the Solar System case) do also present an iron abundance above solar. If we take all stars having companions with periods longer than 1000 days and eccentricities lower than 0.3 we obtain an average <[Fe/H]> of +0.21. A lower (but still high) value of +0.12 is achieved if we do not introduce any eccentricity limit into this sample. We caution, however, that these systems are not necessarily real Solar System analogs.

[7] These are: HD 142, HD 1237, HD 4208, HD 6434, HD 13445, HD 16141, HD 17051, HD 19994, HD 22049, HD 23079, HD 28185, HD 39091, HD 52265, HD 75289, HD 82943, HD 83443, HD 92788, HD 108147, HD 114386, HD 114729, HD 114783, HD 121504, HD 130322, HD 134987, HD 141937, HD 147513, HD 160691, HD 162020, HD 168443, HD 168746, HD 169830, HD 179949, HD 192263, HD 196050, HD 202206, HD 210277, HD 213240, HD 216435, HD 216437, HD 217107, and HD 222582.

It is important to discuss the implications of this result on the planetary formation scenarios. Boss (2002) has shown that the formation of a giant planet as a result of disk instabilities is almost independent of the metallicity; this is contrary to what is expected from a process based in the core accretion scenario. The results presented here, suggesting that the probability of forming a planet (at least of the kind we are finding now) is strongly dependent on the metallicity of the host star, can thus be seen as an argument for the former (traditional) core accretion scenario (Pollack et al. 1996). We note that here we are talking about a probabilistic effect: the fact that the metallicity enhances the probability of forming a planet does not mean one cannot form a planet in a lower metallicity environment. This is mostly due to the fact that other important and unknown parameters, like the proto-planetary disk mass and lifetime, do control the efficiency of planetary formation as well. Furthermore, these results do not exclude that an overlap might exist between the two planetary formation scenarios.

Finally, the small increase seen in the distribution of Fig. 2 (right panel) for low metallicities is clearly not statistically significant, since only one planet host per bin exists in this region of the plot.

### 3.1.1. Measurement precision and [Fe/H]

As discussed in Papers I and II, the rise of the percentage of planets found as a function of the increasing metallicity cannot be the result of any observational bias.

In this sense, particular concern has been shown by the community regarding the fact that a higher metallicity will imply that the spectral lines are better defined. This could mean that the the final precision in radial-velocity could be better for the more "metallic" objects. However, in the CORALIE survey we always set the exposure times in order to have a statistical precision better than the former 7 m s$^{-1}$ instrumental long-term error[8].

A look at Fig. 3, where we plot the mean photon noise error for stars with different [Fe/H] having $V$ magnitudes between 6 and 7, shows us exactly that there is no clear trend in the data. The very slight tendency (metal-rich stars have, in average, measurements with only about 1–2 m s$^{-1}$ better precision than metal poor stars) is definitely not able to induce the strong tendency seen in the [Fe/H] distribution in Fig. 2, specially when we compare it with the usual velocity amplitude induced by the known planetary companions (a few tens of meters-per-second). This also seems to be the case concerning the Lick/Keck planet search programs (D. Fischer, private communication).

### 3.1.2. Primary mass bias

The currently used planet-search surveys are based (in most cases) on samples chosen as volume-limited. However, the criteria to "cut" the sample was usually also based on stellar temperature (i.e. $B-V$ colour).

[8] This value has only recently been improved to about 2–3 m s$^{-1}$ (Queloz et al. 2001; Pepe et al. 2002).

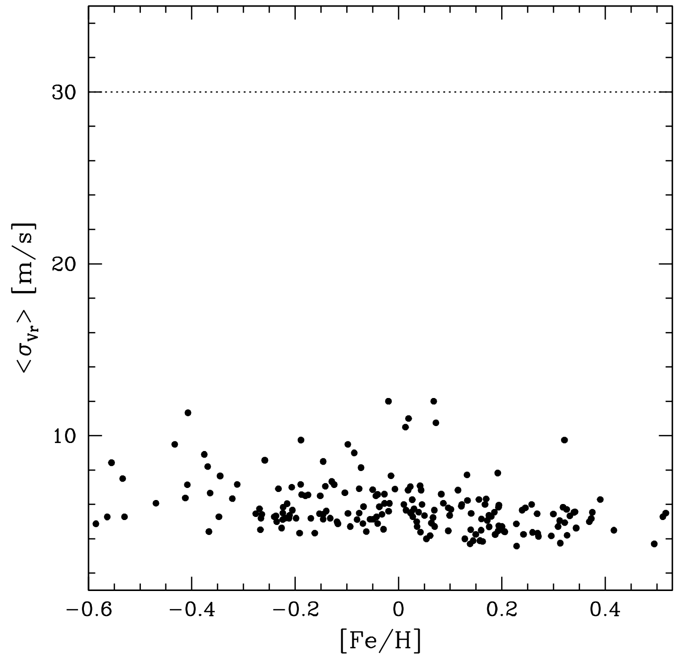


**Fig. 3.** Plot of the mean-photon noise error for the CORALIE measurements of stars having magnitude $V$ between 6 and 7, as a function of the metallicity. This latter quantity was computed using the calibration presented in Santos et al. (2002a). Only a very few planet host stars present radial-velocity variations with an amplitude smaller than 30 m s$^{-1}$ (dotted line).

For a given $B-V$ (i.e. $T_{\rm eff}$), varying the metallicity implies also changing the derived stellar mass. This means that we will have missed in our samples stars with very high [Fe/H] and low mass (they have too high $B-V$), as well as "high" mass objects with low [Fe/H] (too small $B-V$). For example, a 1.3 $M_\odot$ dwarf with [Fe/H] = −0.4 has a temperature of ∼7000 K (Schaller et al. 1992), clearly outside the $B-V$ limits imposed by the CORALIE survey (Udry et al. 2000). On the other side of the mass regime, a 6 Gyr old, 0.6 $M_\odot$ star with solar metallicity has a temperature of only ∼4150 K (Charbonnel et al. 1999); a star of this temperature not only is close to the border of our samples, but it is intrinsically very faint, and thus much more difficult to follow at very high precision.

In other words, the current samples are not really uniform in stellar masses. That fact is well illustrated in Fig. 4: there is clearly a trend that results from the definition of the sample, implying that this latter is constituted (in average) of more metal-poor stars as we go toward a lower mass regime.

This strong bias makes it difficult to study the probability of planetary formation as a function of the stellar mass. It would be very interesting to understand e.g. if higher mass stars, that might have slightly higher disk masses, may eventually form planets more readily[9]. Such studies might be very important to test the planetary formation scenarios.

We can be quite sure, however, that the frequency of planetary formation for a given stellar mass is still increasing

[9] To our knowledge, there is no study to date of the variations in the mass of proto-planetary disks as a function of stellar mass for solar-type stars.

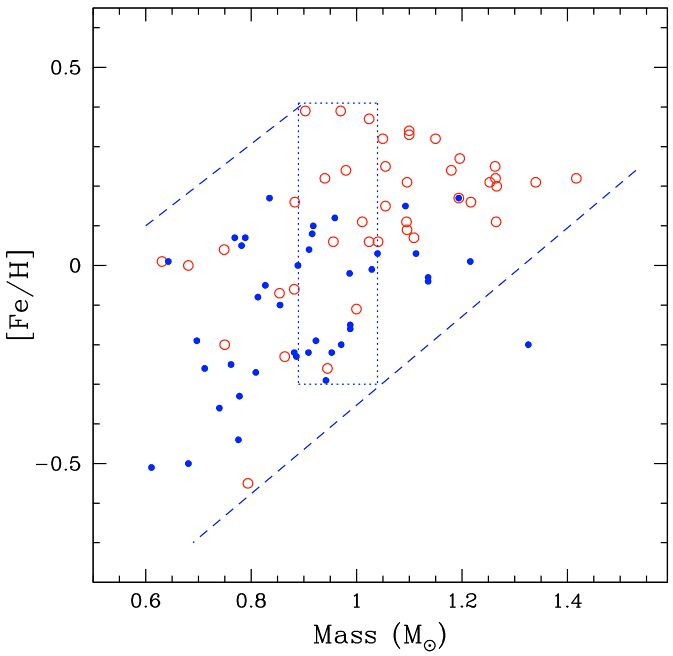


**Fig. 4.** Metallicity vs. stellar mass for planet (open circles) and non-planet host stars (filled dots) included in the CORALIE survey. As we can see from the plot, there is a strong bias related with the cutoff in colour of the sample. The two dashed lines represent simply approximate sampling limits, while the box represents a mass region with no strong biases.

with [Fe/H]. If we look at the plot, the region inside the box is quite clean from the biases discussed above. And as it can be easily seen, in this region planet hosts are still dominating the upper part of the plot. This is true even if for a given mass the higher metallicity stars are also fainter and thus more difficult to measure.

### *3.2. Primordial source as the best explanation*

Two main different interpretations have been given to the [Fe/H] "excess" observed for stars with planets. One suggests that the high metal content is the result of the accretion of planets and/or planetary material into the star (e.g. Gonzalez 1998). Another simply states that the planetary formation mechanism is dependent on the metallicity of the proto-planetary disk: according to the "traditional" view, a gas giant planet is formed by runaway accretion of gas by a ~10 earth-mass planetesimal. The higher the metallicity (and thus the number of dust particles) the faster a planetesimal can grow, and the higher the probability of forming a giant planet before the gas in the disk dissipates.

A third possibility is that the metallicity is in fact favoring the formation of the currently found (in general short period when compared to the Solar System giant planets) exoplanets (Gonzalez 1998). This could fit e.g. into the idea of planetary migration induced by the interaction of the giant planet with a swarm of planetesimals: the higher the metallicity, the higher the number of those minor bodies, and thus the more effective the migration could be. However, the migration mechanisms are not very well understood, and probably more than with the number of planetesimals or the metallicity, the migration rate seems to be related with the disk lifetimes, and to the (gas) disk and planetary masses (Trilling et al. Trilling et al.(2002)). These variables are, however, very poorly known (do they depend e.g. on stellar mass or on the metallicity itself?).

There are multiple ways of deciding between the two former scenarios (see discussion in Paper II), and in particular to try to see if pollution might indeed have played an important role in increasing the metal content of the planet host stars relative to their non-planet host counterparts. Probably the most clear and strong argument is based on stellar internal structure, and in particular on the fact that material falling into a star's surface would induce a different increase in [Fe/H] depending on the depth of its convective envelope (where mixing can occur). This approach, already used by several authors (Laughlin 2000; Santos et al. 2000; Gonzalez et al. 2001; Pinsonneault et al. 2001; Santos et al. 2001a,b; Murray & Chaboyer 2002; Reid 2002), has led to somewhat opposite conclusions.

In Fig. 5 we plot the metallicity for the planet host stars having surface gravity higher than 4.1 dex (to avoid sub-giant stars) against their convective envelope mass[10] (open symbols) as well as for the stars in the comparison sample of Paper II (points). The dashed line represents the mean metallicity for this latter group. The curved line represents the results of adding 8 earth masses of pure iron in the convective envelopes of stars having an initial metallicity similar to the average metallicity of the field star sample.

A look at the points reveals no trend comparable to the one expected if the metallicity excess were mainly a result of the infall of planetary material. In particular, a quick look indicates that the upper envelope of the points is extremely constant. Furthermore, there are no stars with [Fe/H] ≥ +0.5; this should not be the case if pollution were the main cause of the excess metallicity. As shown by Pinsonneault et al. (2001), a similar result is achieved if we replace $M_{\rm conv}$ by $T_{\rm eff}$, since this latter quantity is well correlated with the convective envelope mass. These authors have further shown that even non-standard models of convection and diffusion cannot explain the lack of a trend and thus sustain "pollution" as the source of the high-[Fe/H].

The analysis of Fig. 5 strongly suggests that the high metal content of stars with planets is of "primordial" origin. This is further supported by the fact that the 7 planet host stars which have $\log g$ values lower than 4.1 dex (probably already evolved stars, that have deepened their convective envelopes, diluting every metallicity excess that could be present at the beginning) have a mean metallicity of 0.17 dex, even higher than the 0.13 dex mean value found for all the planet hosts. This result, together with Fig. 2, implies that the metallicity is a key parameter controlling planet formation and evolution, and may have enormous implications on theoretical models (as discussed in Sect. 3.1).

An explanation to the absence of "important" pollution traces can indeed come from arguments based on the timescales of planetary formation. Although still a matter of debate,

[10] This quantity was derived using the equations presented in Murray et al. (2001).

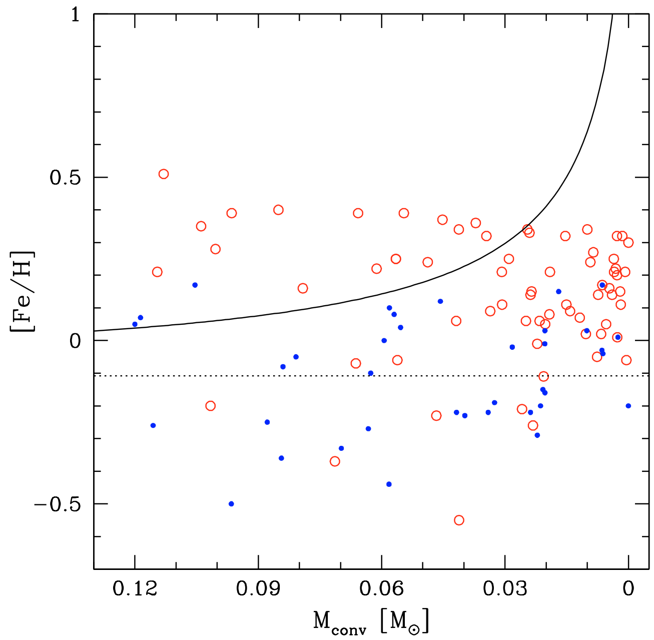


**Fig. 5.** Metallicity vs. convective envelope mass for stars with planets (open symbols) and field dwarfs (points). The [Fe/H] = constant line represents the mean [Fe/H] for the non-planet hosts stars of Fig. 1. The curved line represents the result of adding 8 earth masses of iron to the convective envelope of stars having an initial metallicity equal to the non-planet hosts mean [Fe/H]. The resulting trend has no relation with the distribution of the stars with planets.

near-infrared observations suggest that circumstellar (proto-planetary) disks have lifetimes shorter than 10 Myr (e.g. Haisch et al. 2001, and references therein). Considering that the disappearance of a near-IR disk (i.e. a dust disk) also means that the gas has disappeared (a reasonable assumption), then all the processes connected to the formation of a giant planet must happen before 10 Myr. Taking the example of the Sun, after 10 Myr its convective envelope has ~0.3 $M_{\odot}$ of material[11]. In an extreme case where all the solid material from the disk falls into the star (i.e. about 1 $M_{\rm Jup}$ considering a very massive disk with 0.1 $M_{\odot}$ of gas and dust – Beckwith et al. 1990) but none H and He is accreted, the solar iron abundance would increase by only ~0.1 dex. Even in this case, the pollution would induce a [Fe/H] variation that is still ~0.15 dex lower than the average difference between planet hosts and non-planet hosts. We can thus state that after all pollution is probably not expected to make an important contribution to the total metallicity excess[12]. This is even stressed by the fact that higher mass stars evolve faster, and attain a shallow convective envelope before their lower mass counterparts. This would even strengthen the expected slope in Fig. 5: nothing is seen.

It should be noted however, that we are not excluding that, in some isolated cases, pollution might have been able to alter more or less significantly the global metallicity of the stars. There are some examples supporting that some planet host stars might have suffered a limited amount of "pollution" (e.g. Gonzalez 1998; Smith et al. 2001; Israelian et al. 2001; Laws & Gonzalez 2001; Israelian et al. 2002), although not necessarily able to change considerably the overall metal content (see e.g. Israelian et al. 2001; Pinsonneault et al. 2001; Santos et al. 2002b; Sandquist et al. 2002).

It is also important to mention that here we are interested in discussing the origin of the high metallicity of planet host stars, something that has strong implications into the theories of planetary formation and evolution. The current results do not pretend to discuss the general question of "pollution" in the solar neighborhood, a subject that has seen some results recently published (e.g. Murray et al. 2001; Gratton et al. 2001; Quillen 2002; Gaidos & Gonzalez 2002). In particular, the discovery of possible non-planet host main-sequence binaries with different chemical compositions (Gratton et al. 2001) does not permit to say much regarding the planetary "pollution" problem.

## 4. Correlations with planetary orbital parameters and minimum masses

Some hints of trends between the metallicity of the host stars and the orbital parameters of the planet have been discussed already in the literature. The usually low number of points involved in the statistics did not permit, however, to extract any major conclusions (see Paper II). Today, we dispose of about 80 high-precision and uniform metallicity determinations for planet host stars, a sample that enables us to look for possible trends in [Fe/H] with planetary mass, semi-major axis or period, and eccentricity with a higher degree of confidence. Let us then see what is the current situation.

### *4.1. Planetary mass*

In Fig. 6 (upper left panel) we plot the minimum mass for the "planetary" companions as a function of the metallicity. A simple look at the plot gives us the impression that there is a lack of high mass companions to metal-poor stars. This fact, although not clearly significant, does deserve some discussion.

If we concentrate in the region of $M_2 \sin i < 10\ M_{\rm Jup}$[13] (Fig. 6, upper right panel), the trend mentioned above still remains. As discussed in Udry et al. (2002a), this result can be seen as an evidence that to form a massive planet (at least up to a mass of ~10 $M_{\rm Jup}$) we need more metal-rich disks. For example, the upper plots of Fig. 6 show that except for HD 114762 (a potential brown-dwarf host), all planets with masses above ~4 $M_{\rm Jup}$ orbit stars having metallicities similar or above to solar. This tendency could have to do with the time needed to build the planet seeds before the disk dissipates (if you form more rapidly the cores, you have more time to accrete gas around), or with the mass of the "cores" that will later on accrete gas to form a giant planet[14].

[11] A 1 $M_{\odot}$ solar metallicity star reaches the main-sequence after ~30 Myr.

[12] These facts can even be seen as a constraint for the timescales of disk evolution and giant planet formation.

[13] As shown by Jorissen et al. (2001), this is a probable upper limit for the mass of a planet.

[14] The higher the dust density of the disk, the bigger will be the core mass you might be able to form (e.g. Kokubo & Ida 2002); does this mass influence the final mass of the giant planet?

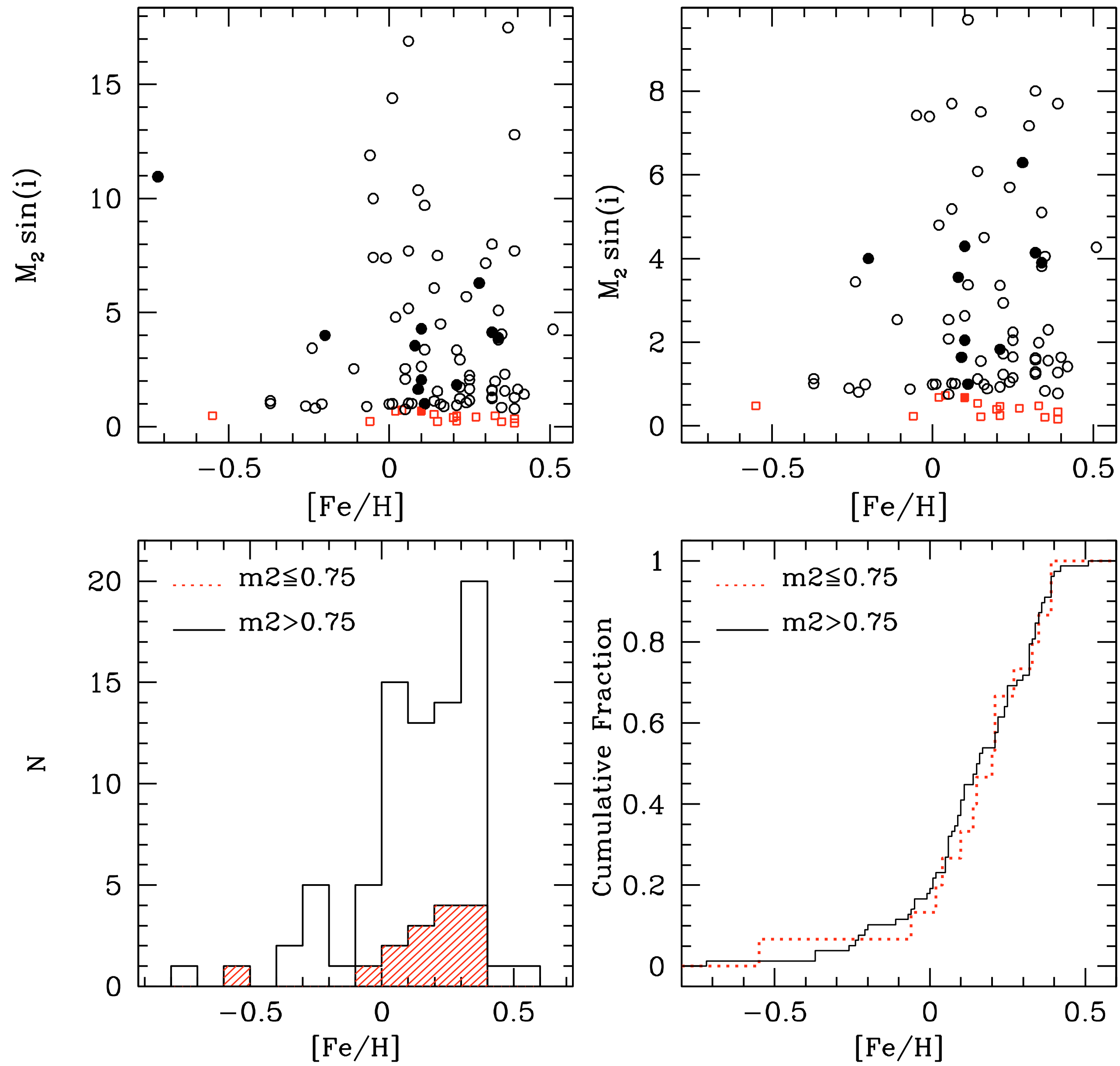


**Fig. 6.** *Upper panels*: metallicity against minimum mass for the planetary companions known to date whose host stars have precise spectroscopic [Fe/H] determinations. The right plot is just a zoom of the upper plot in the region of $M_2 \sin i < 10\ M_{\rm Jup}$ (see text). Different symbols go for the planets with minimum mass above (circles) or below (squares) 0.75 $M_{\rm Jup}$. The filled dots represent planets in stellar systems (Eggenberger et al. 2002). *Lower left*: [Fe/H] distributions for stars with planets less and more massive than 0.75 $M_{\rm Jup}$ (the hashed and open bars, respectively). *Lower right*: cumulative functions of both distributions. A Kolmogorov-Smirnov test gives a probability of ~0.98 that both samples belong to the same distribution.

In the two upper panels, the filled symbols represent planets in multiple stellar systems (Eggenberger et al. 2002). We do not see any special trend for these particular cases.

In the lower panels of Fig. 6 we show the [Fe/H] distribution for the stars with low mass companions for two different companion mass regimes. The chosen limit of 0.75 $M_{\rm Jup}$ as a border takes into account the striking result found by Udry et al. (2002b), in the sense that planets with masses lower than about this value have all periods shorter than ~100 days (these authors see this limit as a strong constraint for the planet migration scenarios). The Kolmogorov-Smirnov test shows that there is no statistically significant difference between these two distributions. Changing the limit from 0.75 $M_{\rm Jup}$ to some other value does not change the significance of the result (nor the shape of the distributions).

### 4.2. Period

Gonzalez (1998) and Queloz et al. (2000) have presented some evidences that stars with short-period planets (i.e. small semi-major axes) may be particularly metal-rich, even amongst the planetary hosts. This fact could be interpreted by considering that the migration process is able to pollute the stellar convective envelope (Murray et al. 1998), that the formation

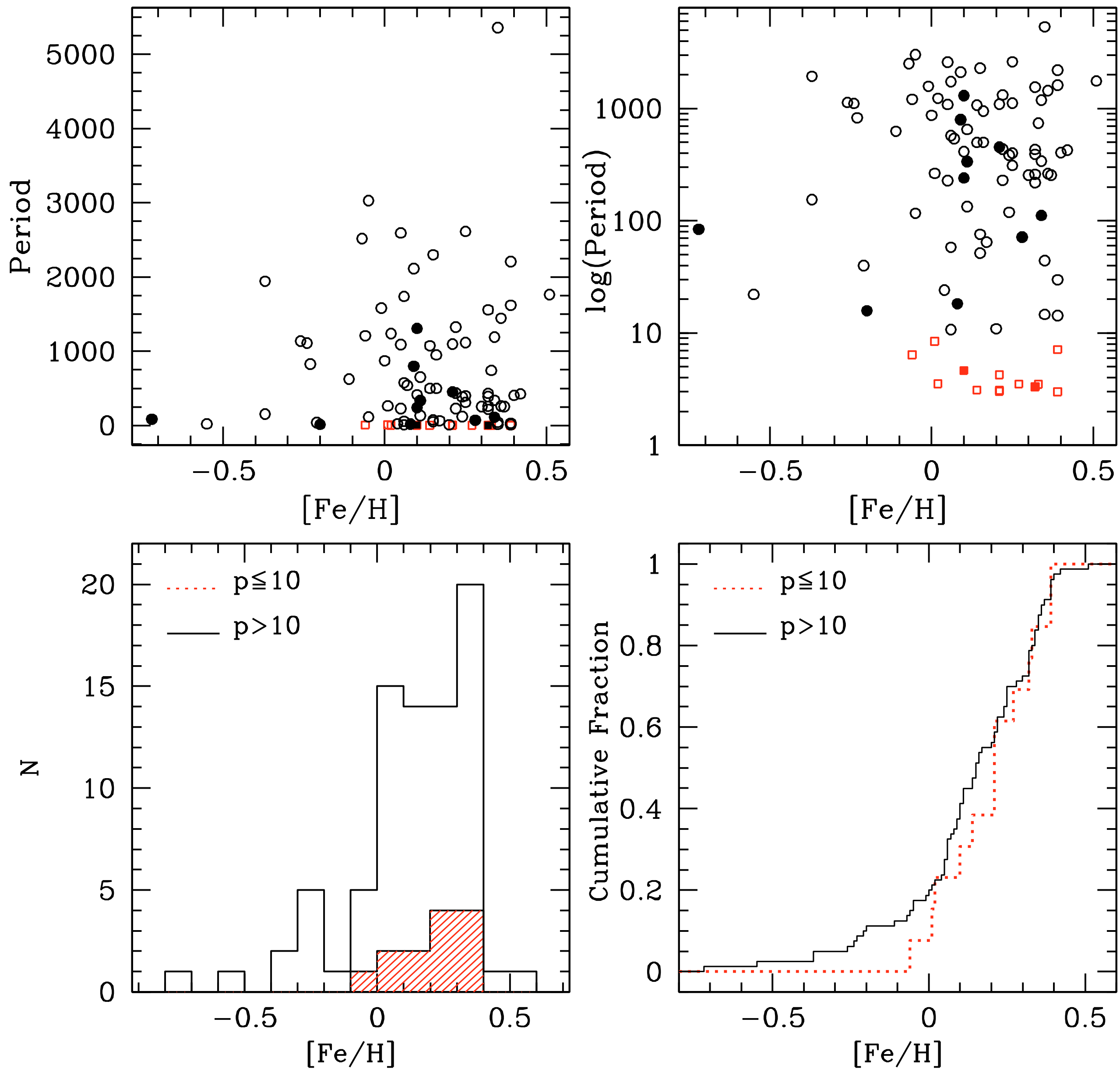


**Fig. 7.** *Upper panels*: metallicity against orbital period for the planetary companions known to date and whose host stars have precise spectroscopic [Fe/H] determinations in linear (left) and log scales (right). Different symbols are used for planets in orbits having periods longer and smaller than 10 days. The filled dots represent planets in stellar systems (Eggenberger et al. 2002). *Lower left*: [Fe/H] distributions for stars with planets with orbital periods shorter and longer than 10 days (the hashed and open bars, respectively). *Lower right*: cumulative functions of both distributions. A Kolmogorov-Smirnov test gives a probability of ~0.75 that both samples belong to the same distribution.

of close-in planets is favored by the metallicity, or that the subsequent inward orbital evolution of a newborn planet may be favored by the higher metallicity of the disk (e.g. by the presence of more planetesimals/planets with which the planet can interact). The number of planets that were known by that time was, however, not sufficient for us to take any definitive conclusion. In fact, in Paper II we have not found that this trend was very significant, although there was still a slight correlation.

In Fig. 7 (upper panels) we plot the metallicity against the orbital period for the planets whose stars have precise spectroscopic metallicity determinations. In the plot, the squares represent planet hosts having companions in orbits shorter than 10 days ("hot jupiters"), while circles represent planets with longer orbital period. As we can see from the plots, there seems to be a small tendency for short period planets to orbit more metal-rich stars (see also the two lower panels). Or, from another point of view, the distribution for longer period systems seems to have a low metallicity tail, not present for the shorter period case (see the lower left panels). This tendency is clearly not significant, however (the Kolmogorov-Smirnov probability that both samples belong to the same population is of 0.75).

Changing the limits does not bring further clues on any statistically significant trend. In particular, setting the border at around 100 days, a value that seems to have some physical sense (companions to stars having periods shorter than this limit have statistically lower masses – Udry et al. 2002b) does not change the conclusions. We have further tried to investigate if the shape of the metallicity distributions changes if we consider planet hosts having companions with a different range of orbital period. A very slight trend seems to appear if we separate stars having companions with periods longer and shorter than 1 year, in the sense that the former's [Fe/H] distribution seems to be a bit more flat. But at this moment this is far from being significant.

We note, however, that the two lowest metallicity stars in the samples are both in the <100 day period regime. These two points give us the impression (in the upper-left plot) that there do not seem to exist any long period systems around low metallicity stars. This impression disappears, however, if we plot the period in a logarithmic scale (upper-right panel). No further conclusions can be taken at this moment.

As before, in the two upper panels, the filled symbols represent planets in stellar systems (Eggenberger et al. 2002). We do not see any special trend for these particular cases.

The lack of a clear relation between orbital period and stellar metallicity might imply that the migration mechanisms are reasonably independent of the quantity of metals in the disk. This result might thus fit better into the scenarios based on the migration of the planet through a gas disk (e.g. Goldreich & Tremaine 1980; Lin et al. 1996) when compared to the scenarios of migration due to interaction with a disk of planetesimals (Murray et al. 1998).

On the other hand, lower mass planets are supposed to migrate faster than their more massive counterparts, since these latter open more easily a gap in the disk, thus halting their (type-II) migration (Trilling et al. Trilling et al.(2002)). This is observationally supported by the discovery that there are no massive planets in short period orbits (Zucker & Mazeh 2002; Udry et al. 2002a), and by the clear trend showing that planets less massive than ~0.75 $M_{\mathrm{Jup}}$ all follow short period trajectories (Udry et al. 2002b). If the low metallicity stars are only able to form low-mass planets (a slight trend suggested in the last section), metal-poor stars should have preferentially "short"[15] period planets.

### 4.3. Eccentricity

It might also be interesting to explore whether there is any relation between the eccentricity of the planetary orbits and the stellar metallicity. Such an analysis is presented in Fig. 8.

As it can be seen, no special trends seem to exist. There is a slight suggestion that all the low metallicity objects have intermediate eccentricities only. In other words, the more eccentric planets seem to orbit only stars with metallicity higher or comparable to solar, and on the opposite side of the eccentricity distribution, there seems also to be a lack of low eccentricity planets around metal-poor stars.

However, as can also be seen in Fig. 8 (histogram and cumulative functions), this result is not statistically significant. We have tried to change the limits of eccentricity for the two [Fe/H] distributions. No further conclusions can be taken.

[15] With short we refer here to planets having periods that are, in average, shorter than the ones found around more metal-rich stars.

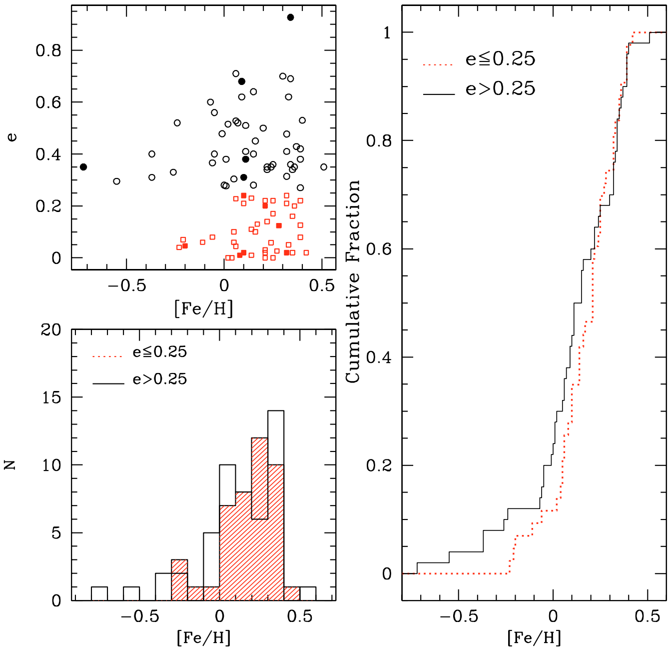


**Fig. 8.** *Upper left*: metallicity against orbital eccentricity for the known planetary companions whose host stars have precise spectroscopic [Fe/H] determinations. Different symbols are used for planets in orbits having eccentricity higher or smaller than 0.25. The filled dots represent planets in stellar systems (Eggenberger et al. 2002). *Lower left*: [Fe/H] distributions for stars with planets with eccentricities lower and higher than 0.25 (the hashed and open bars, respectively). *Right*: cumulative functions of both distributions. A Kolmogorov-Smirnov test gives a probability of ~0.38 that both samples belong to the same distribution.

## 5. *U*, *V*, *W*, and metallicity

### 5.1. Kinematics of stars with planets

There are only a few studies in the literature on the kinematics of planet host stars (Gonzalez 1999; Reid 2002; Barbieri & Gratton 2002). None of them, however, has made use of a completely unbiased sample to compare planet and non-planet host stars. To fill this gap, we have analyzed the spatial velocities distributions and velocity dispersions for the subsample of extra-solar planet host stars that are included in the CORALIE sample, and have compared this results with space velocities for ~1000 dwarfs that make part of the CORALIE survey (Udry et al. 2000) and have precise radial-velocity measurements. We have restricted the planet sample to only those planets belonging to the CORALIE sample in order to minimize the biases when trying to compare planet and non-planet host stars.

The $U$, $V$, and $W$ velocities[16] were computed using CORALIE radial velocities, as well as coordinates and proper motions from Hipparcos (ESA 1997)[17]. The convention used is so that $U$, $V$ and $W$ are positive in the direction of the

[16] $U$, $V$ and $W$ represent the usual spatial velocities of a star in the direction of the the galactic center, galactic rotation, and perpendicular to the galactic plane, respectively.

[17] The values of $U$, $V$ and $W$ for the planet host stars will be available at the 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/398/363`

**Table 3.** Average space velocities and their dispersions.

| Velocities (km s$^{-1}$) | Planet hosts | CORALIE sample |
|---|---|---|
| $< U_{\rm LSR} >$ | 3.2 ± 6.0 | −2.5 ± 1.2 |
| $< V_{\rm LSR} >$ | −17.2 ± 3.9 | −18.3 ± 0.8 |
| $< W_{\rm LSR} >$ | −1.6 ± 2.2 | −2.6 ± 0.6 |
| $\sigma(U_{\rm LSR})$ | 37.9 ± 4.3 | 37.9 ± 0.9 |
| $\sigma(V_{\rm LSR})$ | 24.5 ± 2.8 | 25.4 ± 0.6 |
| $\sigma(W_{\rm LSR})$ | 13.8 ± 1.6 | 18.9 ± 0.4 |

Here we use $\sigma/\sqrt{N-1}$ for the errors in $<U_{\rm LSR}>$, $<V_{\rm LSR}>$, and $<W_{\rm LSR}>$, and $\sigma/\sqrt{2\,N-1}$ for the errors in $\sigma(U_{\rm LSR})$, $\sigma(V_{\rm LSR})$, and $\sigma(W_{\rm LSR})$; N equals 990 for the CORALIE sample, and 41 for the planet sample.

galactic center, the galactic rotation, and the north galactic pole, respectively. We have then corrected the velocities with respect to the Solar motion relative to the LSR adopting $(U_{\rm LSR},V_{\rm LSR},W_{\rm LSR})_{\odot}$ = (10,6,6) km s$^{-1}$ (e.g. Gonzalez 1999).

In Fig. 9 we plot the classical $U_{\rm LSR}$–$V_{\rm LSR}$, $U_{\rm LSR}$–$W_{\rm LSR}$, and $V_{\rm LSR}$–$W_{\rm LSR}$ diagrams (left plots) for planet hosts (dots) and non-planet hosts (small points), as well as the cumulative functions of $U_{\rm LSR}$, $V_{\rm LSR}$ and $W_{\rm LSR}$ (right plots) for the two samples. As we can see, there is no major difference between the two groups of points. This is supported in all cases by a Kormogorov-Smirnov test. The only special feature to mention in this plot is that the $W_{\rm LSR}$ velocity seems to have a greater dispersion for non-planet hosts than for planet hosts (this can be seen from the cumulative functions of $W_{\rm LSR}$ for the two samples).

As discussed by Raboud et al. (1998) – see also review by Grenon (2000) – Galactic dynamic models imply that stars coming from the inner disk and influenced by the Galactic bar should present a lower dispersion in $W_{\rm LSR}$ and a higher $U_{\rm LSR}$. Although the former of these two trends is suggested by our data, the higher $U_{\rm LSR}$ observed for the planet hosts (with respect to the other CORALIE sample stars) is not significant (see also Table 3).

In Table 3 we list the mean $U_{\rm LSR}$, $V_{\rm LSR}$, and $W_{\rm LSR}$ velocities and their dispersions for the two groups of stars analyzed. As we can see, besides the lower dispersion in $W_{\rm LSR}$ for the planet host sample, the two groups do not seem to differ considerably. The mean total space velocity for planet and non-planet hosts (42.2 ± 4.4 km s$^{-1}$ and 45.6 ± 0.8 km s$^{-1}$, respectively), and their dispersions (27.7 ± 3.1 km s$^{-1}$ and 26.4 ± 0.6 km s$^{-1}$) also do not show any special trend.

### 5.2. Kinematics vs. [Fe/H]

In Fig. 10 we further compare the metallicity as a function of the space velocities for the same two samples described above. In the right panels we plot [Fe/H] as a function of $U_{\rm LSR}$, $V_{\rm LSR}$, and $W_{\rm LSR}$, and in the left plots we have the cumulative functions for $U_{\rm LSR}$, $V_{\rm LSR}$, and $W_{\rm LSR}$ as in Fig. 9, but this time separating the stars with [Fe/H] higher than solar (right panel) and lower than solar (left panel). Again, no statistically significant conclusions can be drawn. Stars with planets seem to occupy basically the metal-rich envelope of the $U_{\rm LSR}$, $V_{\rm LSR}$, and $W_{\rm LSR}$ vs. [Fe/H] plots.

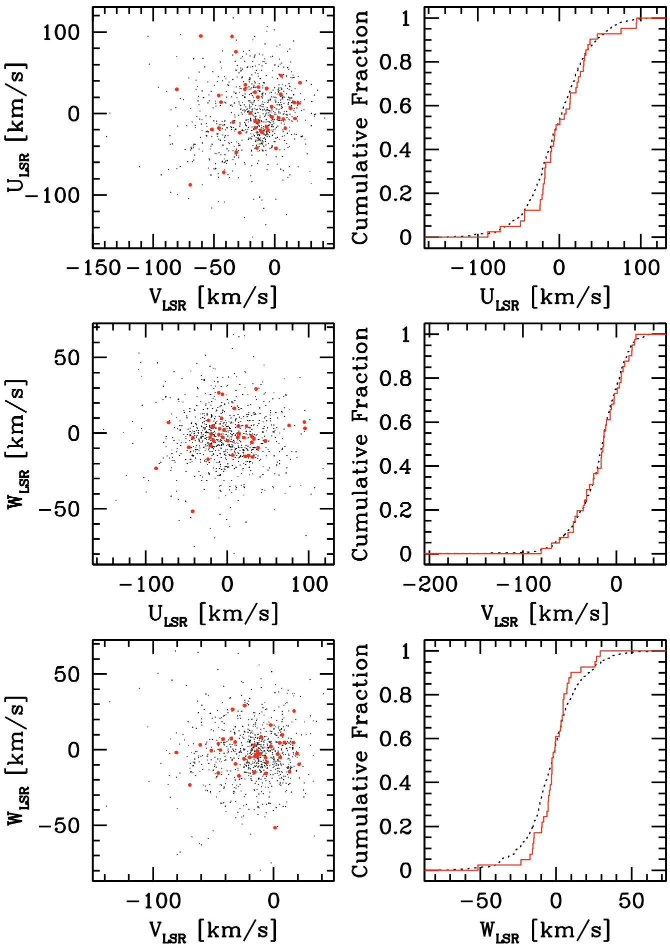


**Fig. 9.** *Left*: $U_{\rm LSR}$–$V_{\rm LSR}$, $U_{\rm LSR}$–$W_{\rm LSR}$, and $V_{\rm LSR}$–$W_{\rm LSR}$ diagrams for planet hosts (filled dots) and stars in the CORALIE sample (see text for more details). *Right*: cumulative functions of $U_{\rm LSR}$, $V_{\rm LSR}$, and $W_{\rm LSR}$ for the two samples (planet hosts are the filled line, and the CORALIE sample is denoted by the dotted line).

In a few words, within the statistical significance of our sample, we can say that for a given metallicity interval, the space velocity distribution of the planet host stars are basically the same as the one found for the whole planet search sample.

## 6. Concluding remarks

In this article we present a detailed spectroscopic analysis of more than 50 extra-solar planet host stars (to be added to the previously derived results), with the main goal of looking for correlations between the stellar metallicity and the planetary orbital properties. We have further tried to verify if planet host stars have any anomaly concerning the space velocities. The main conclusions of the article can be summarized in the following way:

– We confirm previous results that have shown that planet host stars are metal-rich when compared to the average local field dwarfs. The addition of the new data, and the comparison of the planet host star metallicity with the one for a large volume limited sample of field dwarfs, even strengthens the statistical significance of the result. Furthermore,

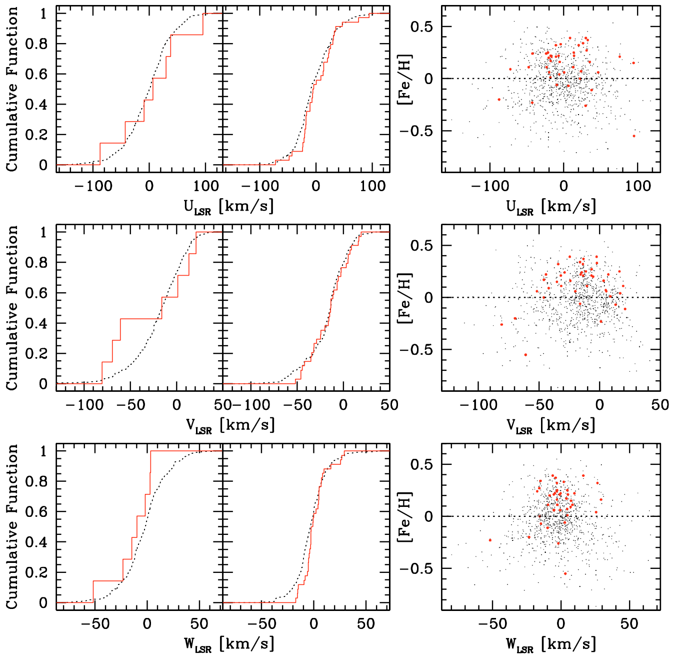


**Fig. 10.** *Right*: metallicity as a function of the space velocities for planet and non-planet hosts. *Left*: cumulative functions for the two samples but dividing the stars in metal rich ([Fe/H] > 0.0 – right panels) and metal poor ([Fe/H] ≤ 0.0 – left panels). Symbols as in Fig. 9.

it is shown that this result is still true if we compare planet and non-planet host stars within a given stellar mass regime.

- Stars with companions in the mass regime 20 $M_{\rm Jup} > M >$ 10 $M_{\rm Jup}$ present a wide variety of metallicities, and are up to now indistinguishable from the stars having lower mass companions. This result might be telling us that these "higher" mass companions were formed in the same way as their lower mass counterparts. The same situation is found for systems with more than one planet, and for planets in stellar binaries.
- We also confirm previous results suggesting that the probability of finding a planet increases with the metallicity of the star. At least 7% of the stars in the CORALIE planet-search sample having [Fe/H] between 0.3 and 0.4 dex have a planetary companion. This frequency falls to a value of less then 1% for stars with solar metallicity. We have also shown that this result cannot be related to any observational bias.
- Our results also strongly support the "primordial" source as the key parameter controlling the high metal content of the planet host stars. "Pollution" does not seem to be an "important" mechanism.
- We have explored the relation between the metallicity of the host stars and the orbital parameters of the planets. We have found some indications (not statistically significant) that metal-poor stars might be mainly able to form low mass planets, a result previously discussed by Udry et al. (2002a). In an even less significant sense, the low [Fe/H] stars seem to be orbited (in average) by planets having intermediate eccentricities. As for the orbital period, very short period planets also seem to orbit preferentially metal-rich stars, but the difference with respect to their longer period counterparts is clearly not significant. In any case, the results seem to be telling us that the metallicity is not playing a very important role in determining the final orbital characteristics of the discovered exoplanets. The metal content of the disk does not seem to be a crucial parameter controlling the migration processes. But it will be very interesting to follow the results as more low mass and long period planets, more similar to the Solar System giants, become common in the planet discovery lists.
- No significant differences are found when comparing planet hosts and non-planet hosts in plots relating $U$, $V$, $W$ and [Fe/H]. In general, planet host stars seem to occupy the metal-rich envelope of the plots.

The results presented above seem to support a scenario where the formation of giant planets, or at least of the type we are finding now, is particularly dependent on the [Fe/H] of the primordial cloud. In other words, and as already discussed in Paper II, the metallicity seems to play a crucial role in the formation of giant planets, as it is indicated by the shape of the metallicity distribution.

Our results further support the core accretion scenario (e.g. Pollack et al. 1996) against the disk instability model (Boss 2000) as the "main" mechanism of giant-planetary formation. In fact, Boss (2002) has shown that contrarily to the core-accretion models, the efficiency of planetary formation in the case of the disk instability should not strongly depend on the metallicity of the disk. In other words, if that were the case, we should probably not see an increase in the frequency of planets as a function of the metallicity: such a trend is clearly seen in our data. We note, however, that the current data does not discard that both situations can occur.

In the future, it is important to try to explore and compare the abundances of other metals (besides light elements) in planet and non-planet host stars. In this context, there are already a few results published (Santos et al. 2000; Smith et al. 2001; Gonzalez et al. 2001; Takeda et al. 2001; Sadakane et al. 2002), but up to now there have been no published uniform studies, a matter that clearly makes a comparison difficult. We are currently working on this problem, in order to offer a uniform comparison between planet and non-planet hosts for other elements in a similar way as was done here for [Fe/H].

As seen in the current work, the increase in the number of known exoplanets is permitting the development of different sorts of statistical studies. However, in face of the number of variables that might be interrelated (e.g. metallicity, and the various orbital parameters) it is still difficult to take any statistically significant conclusions. A clear improvement of the current situation can only be achieved if the kind of studies presented here are continued as new planets are found.

*Acknowledgements.* We would like to thank Nami Mowlavi for the important help in determining the stellar masses, and C. Perrier for obtaining ELODIE spectra for two of the stars. We wish to thank the Swiss National Science Foundation (Swiss NSF) for the continuous support to this project. Support from Fundação para a Ciência e

Tecnologia (Portugal) to N.C.S. in the form of a scholarship is gratefully acknowledged.

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