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The HARPS search for southern extra-solar planets

XXI. Three new giant planets orbiting the metal-poor stars HD 5388, HD 181720, and HD 190984⋆,⋆⋆

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ABSTRACT

We present the discovery of three new giant planets around three metal-deficient stars: HD 5388 b (1.96 $M_{\rm Jup}$), HD 181720 b (0.37 $M_{\rm Jup}$), and HD 190984 b (3.1 $M_{\rm Jup}$). All the planets have moderately eccentric orbits (ranging from 0.26 to 0.57) and long orbital periods (from 777 to 4885 days). Two of the stars (HD 181720 and HD 190984) were part of a program searching for giant planets around a sample of ∼100 moderately metal-poor stars, while HD 5388 was part of the volume-limited sample of the HARPS GTO program. Our discoveries suggest that giant planets in long period orbits are not uncommon around moderately metal-poor stars.

Key words. planets and satellites: formation – stars: abundances – stars: fundamental parameters – planetary systems – techniques: radial velocities – techniques: spectroscopic

1. Introduction

The discovery of about 400 exoplanets orbiting solar-type stars has opened a number of questions about the origin of the new-found planets (for a review see Udry & Santos 2007). The theories of planet formation are thus confronted with new and fascinating problems, whose solution may give us a new insight into the processes of planet formation and evolution.

Two major theories have been proposed to explain the formation of the discovered giant planets. On the one hand, the "traditional" core-accretion model (Pollack et al. 1996), more recently improved to include the effects of planet migration and disk evolution (e.g. Ida & Lin 2004; Mordasini et al. 2009), suggests that giant planets are formed by the accretion of gas around a pre-formed metal-rich (icy) core. On the other hand, the so-called disk instability models advocate that giant planets can be formed by the direct collapse of gas and dust in the proto-planetary disk (Boss 1997).

Based on recent observational results (see discussion in Udry & Santos 2007) the core-accretion model is presently favoured. However, the existence of giant planets at more than 20 AU from their host stars (Kalas et al. 2008; Marois et al. 2008) was recently suggested to be more easily explained by the disk instability model (Dodson-Robinson et al. 2009). To understand which of the two processes of giant planet formation best explains the detected population of exoplanets we need more observational data.

The solution to this problem may include the understanding of the well known stellar metallicity-giant planet correlation. It is known that giant planets are more easily found orbiting metal-rich dwarfs (Gonzalez 1997; Santos et al. 2004b; Fischer & Valenti 2005). This result strongly favors the core-accretion model to explain the formation of the majority of the giant planets discovered so far (e.g. Matsuo et al. 2007). Still, it is also known that planet formation is not completely inhibited around metal-poor dwarfs (e.g. Cochran et al. 2007; Santos et al. 2007). The small number of planets detected around metal-poor objects still prevents a clear analysis of the low metallicity tail of the abundance distribution of planet-host stars though.

To bridge this gap, a number of projects have been started to search for planets in metal-poor samples (Sozzetti et al. 2006; Cochran et al. 2007; Santos et al. 2007). In addition to these, large volume-limited samples of solar neighborhood stars are

⋆ Based on observations collected at the La Silla Parana Observatory, ESO (Chile) with the HARPS spectrograph at the 3.6-m telescope (ESO runs ID 72.C-0488 and 082.C-0212).

⋆⋆ Tables 3–5 (with the radial-velocities) are only available in electronic form 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/512/A47 adding new planets to the lists, some of them orbiting metal-poor stars.

In this paper we present the detection by two HARPS GTO programs of three new planets which orbit metal-poor stars. One of these was discovered as part of a large volume-limited survey (Pepe et al. 2004) for giant planets. The remaining two are the second and third planets discovered in the HARPS metal-poor sample (Santos et al. 2007). In Sects. 2 and 3 we briefly present our sample as well as the parameters of the host stars. In Sect. 4 we present the radial-velocity measurerements and the fitted orbital solutions. We conclude in Sect. 5, where we discuss the implications of the present findings.

2. Sample and observations

The planets presented in this paper were discovered orbiting stars which were followed as part of two different HARPS GTO programs. The first consists of a sample of ∼850 solar-type stars in a volume-limited complement (up to 57.5 pc) of the "closer" CORALIE sample (Udry et al. 2000). More details about this sample can be found in Naef et al. (2007). The second program consists of a sample of ∼100 metal-poor dwarfs that was searched for the presence of giant planets. A description of this latter sample can be found in Santos et al. (2007).

Observations of all the targets were obtained during the Guaranteed Time Observations GTO (Mayor et al. 2003). For HD 181720 and HD 190984, however, complementary observations were obtained in a separate HARPS program whose goal was to search for neptune-mass planets orbiting moderately metal-poor stars.

Radial-velocities were derived using the latest version of the HARPS pipeline. From each spectrum, other parameters of the HARPS cross-correlation function (CCF) such as the bisector inverse slope (BIS – Queloz et al. 2001) were also derived.

Most of the radial-velocity measurements were not done in the simultaneous ThAr calibration mode. A strategy to average out the noise due to stellar oscillations (Santos et al. 2004a) was also not used in most of the measurements, since this is not required for the detection of giant planets (the main goal of the two mentioned programs). We can thus expect the residuals around the orbital solutions to be above 1 m s^{-1}. This is particularly true for early-G and late-F stars (like our targets), since the oscillation and granulation noise is stronger for these objects (Dumusque et al. 2009, in prep.).

3. Stellar parameters

The global stellar parameters for each of the planet-host stars analyzed in the present paper are listed in Table 1.

The spectral type, m_v, $B-V$, and parallax (and derived distance), were taken from the Hipparcos catalog (ESA 1997), except for HD 190984 (see discussion below). M_V, L, and the stellar radius were computed from the above values, using a bolometric correction from Flower (1996) and the $T_{\rm eff}$ obtained from the spectroscopy (see below).

The values for the effective temperature, surface gravity, microturbulence, and iron abundance were obtained using the high-S/N combined HARPS spectra for each target. The values were derived following the method and line-lists described in Santos et al. (2004b) and Sousa et al. (2008). The final values, together with their errors, are presented in Table 1. We refer the reader to these authors for more details.

Table 1. Stellar parameters for the stars analyzed in the present paper.

Parameter	HD 5388	HD 181720	HD 190984
Spectral type	F6V	G1V	F8V
m_v	6.73	7.84	8.76
$B-V$	0.500	0.599	0.579
Parallax [mas]	18.77 ± 0.96	17.88 ± 1.31	9.8 ± 2.6†
Distance [pc]	53 ± 3	56 ± 4	$103^{+37\dagger}_{-21}$
M_v	3.10	4.10	3.71
$L[L_{\odot}]$	4.60	1.94	2.69
Radius [$R_{\odot}$]	1.91	1.39	1.53
$\log R'_{\rm HK}$	−4.98	−5.01	−5.01
$v \sin i$ [km s^{-1}]	4.2	1.5	3.4
$T_{\rm eff}$ [K]	6297 ± 32	5781 ± 18	5988 ± 25
$\log g$	4.28 ± 0.06	4.24 ± 0.15	4.02 ± 0.22
$\xi_{\rm t}$	1.57 ± 0.04	1.17 ± 0.04	1.48 ± 0.03
[Fe/H]	−0.27 ± 0.02	−0.53 ± 0.02	−0.48 ± 0.06
Mass [$M_{\odot}$]	1.21	0.92	0.91

Notes. $^{(\dagger)}$ Derived in this paper (see text).

Stellar masses were also derived by interpolating the theoretical isochrones of Girardi et al. (2000)[1], using $T_{\rm eff}$ and [Fe/H] obtained from the spectroscopy, as well as V and the parallax from the Hipparcos catalog. We estimate that the uncertainties are on the order of 10% due to the errors in the input parameters and also due to different systematic effects (Fernandes & Santos 2004).

Values for the projected rotational velocity, $v \sin i$, and the stellar activity level (based on the Ca II H and K lines) were derived from the HARPS spectra following the general recipes described in Santos et al. (2000) and Santos et al. (2002), respectively. The computed values show that all targets have a low chromospheric activity level.

3.1. HD 5388 (HIP4311)

Masana et al. (2006) found an effective temperature and stellar radius of 6201 K and 1.91 $R_{\odot}$ for this star in very good agreement with the values derived in the present paper (6297 K and 1.91 $R_{\odot}$). This value for $T_{\rm eff}$ is similar to the one derived by Nordström et al. (2004, 6208 K) and to the value obtained using the ($B-V$, [Fe/H]) calibration of Sousa et al. (2008, 6260 K). The stellar metallicity derived in the present paper (−0.27) agrees also perfectly with the one derived by these latter authors (−0.25). These values are slightly above (but still compatible) with the metallicity (−0.34) computed using a calibration of the HARPS Cross-Correlation Function (see similar calibration for CORALIE – Santos et al. 2002). The derived activity value of $\log R'_{\rm HK} = -4.98$ suggests that this star is not chromospherically active.

3.2. HD 181720 (HIP95262)

The spectroscopic effective temperature obtained for this star (5781 K) superbly agrees with the values of 5776, 5745, and 5800 K, derived using the calibration presented in Sousa et al. (2008), and obtained by Masana et al. (2006) and Nordström et al. (2004), respectively. The metallicity of −0.53 is also

[1] See the web interface at http://stev.oapd.inaf.it/cgi-bin/param

Table 2. Elements of the fitted orbits.

	HD 5388	HD 181720	HD190984	
P	777 ± 4	956 ± 14	4885 ± 1600	[d]
T	2 454 570 ± 9	2 453 631 ± 30	2 449 572 ± 1600	[d]
a	1.76	1.78	5.5	[AU]
e	0.40 ± 0.02	0.26 ± 0.06	0.57 ± 0.10	
V_r	39.308 ± 0.001	−45.3352 ± 0.0004	20.269 ± 0.004	[km s^{-1}]
ω	324 ± 4	177 ± 12	318 ± 5	[degr]
K_1	41.7 ± 1.6	8.4 ± 0.4	48 ± 1	[m s^{-1}]
$f_1(m)$	4.47×10^{-9}	0.053×10^{-9}	30.95	[$M_\odot$]
σ(O−C)	3.33	1.37	3.44	[m s^{-1}]
N	68	28	47	
$m_2 \sin i$	1.96	0.37	3.1	[$M_{\rm Jup}$]

similar to the one derived by Nordström et al. (−0.49), and also to the value of −0.54 obtained using a calibration of the HARPS CCF. The low activity level of this star ($\log R'_{\rm HK} = -5.01$) as measured from the HARPS spectra is also supported by previous measurements of the $\log R'_{\rm HK}$ index of −5.07 and −5.00 derived by Wright (2004) and Henry et al. (1996), respectively.

3.3. HD 190984 (HIP99496)

The effective temperature derived for HD 190984 (5988 K) agrees well with the value found by Masana et al. (2006, 5921 K) and Nordström et al. (2004, 5902 K), as well as with the value obtained using the calibration of Sousa et al. (2008, 5868 K). The stellar metallicity derived by our spectroscopic analysis (−0.48) is also in excellent agreement with the value listed by Nordstrom et al. ([Fe/H] = −0.47), and slightly above the value derived using the HARPS CCF (−0.64). The chromospheric activity level, as calculated using the HARPS spectra, shows that HD 190984 is inactive. The surface gravity for this star hints that it may be slightly evolved.

The parallax value for this star listed in the Hipparcos catalog ($\pi = 5.28 \pm 1.25$ mas) has a large uncertainty. This situation remains true if we take the more recent parallax value derived by van Leeuwen (2007, $\pi = 5.45 \pm 1.11$). Making use of the Hipparcos parallax we found values for M_v and luminosity of 2.37 and 9.3, respectively. These values seem to contradict the results from our detailed spectroscopic analysis.

We have thus decided to rederive the parallax using an iterative procedure that makes use of Eq. (1) in Santos et al. (2004b), the relation between luminosity, radius, and parallax, and the isochrones of Girardi et al. (2000). We first fixed the bolometric correction and the visual magnitude of the star to the values derived by the calibration of Flower (1996) and the value listed in the Hipparcos catalog, respectively. An initial value for the stellar mass was also obtained using the Hipparcos parallax and V magnitude and the metallicity and temperature derived from spectroscopy. Then, using this value for the mass (with an associated error of 10%), the effective temperature and the surface gravity (and their respective errors), we took 1000 randomly selected Gaussian distributed values for these three parameters. These were then used to create a distribution for the stellar luminosities and stellar radii, which where in turn used to calculate a distribution of parallaxes. Once the new value for the parallax was derived, a new mass was obtained. Following this procedure we found a convergence after only three iterations. The final value for the parallax (see Table 1) is significantly different from the value listed in the Hipparcos catalog. The reason for this discrepancy is not clear to us.

4. Radial-velocities

4.1. HD 5388

Sixty-eight radial-velocity measurements of HD 5388 were obtained between September 2003 and September 2009 (Table 3)[2]. The data show a clear periodic signal that can be well fitted with a Keplerian function with a period of 777 days, an eccentricity of 0.40, and a semi-amplitude of 42 m s^{-1}. This signal is compatible with the radial-velocity variation induced by a 1.96 Jupiter mass companion orbiting the 1.21 $M_\odot$ dwarf HD 5388 (see Table 2 and Fig. 1).

The analysis of the residuals of the Keplerian fit (3.33 m s^{-1}) suggest that some residual trends may be present in the data. However, we find no clear evidence for any extra component. In any case, the average error of the individual data points is 2.8 m s^{-1}, only 1.8 m s^{-1} below the residuals (after quadratic subtraction). Given the observational strategy used, the relatively high value for the stellar projected rotational velocity and the spectral type of the star, this value is likely not significant (see Sect. 2).

To understand if the periodic radial-velocity signal observed could have a non-planetary origin (see e.g. Saar & Donahue 1997; Queloz et al. 2000; Santos et al. 2002, 2010), we also analyzed the bisector inverse slope (BIS) of the cross-correlation Function (Queloz et al. 2001). No correlation between radial-velocity (RV) and BIS is seen (Fig. 4), which suggests that stellar activity of stellar blends cannot explain the RV variation observed. Together with the low activity level of the star, we conclude that the 777-day orbital period observed can be better explained by the presence of a Jupiter-like planet which orbits HD 5388.

4.2. HD 181720

A total of 28 radial-velocity measurements of HD 181720 were taken between September 2003 and September 2009 (Table 4). The velocities show a clear low amplitude and long period variation (Fig. 2). The data are well fitted with a single Keplerian function with a period of 956 days, an eccentricity of 0.26, and

[2] Tables 3–5, with the HARPS radial-velocities for HD 5388, HD 181720, and HD 190984, respectively, are only available in electronic form at the CDS.

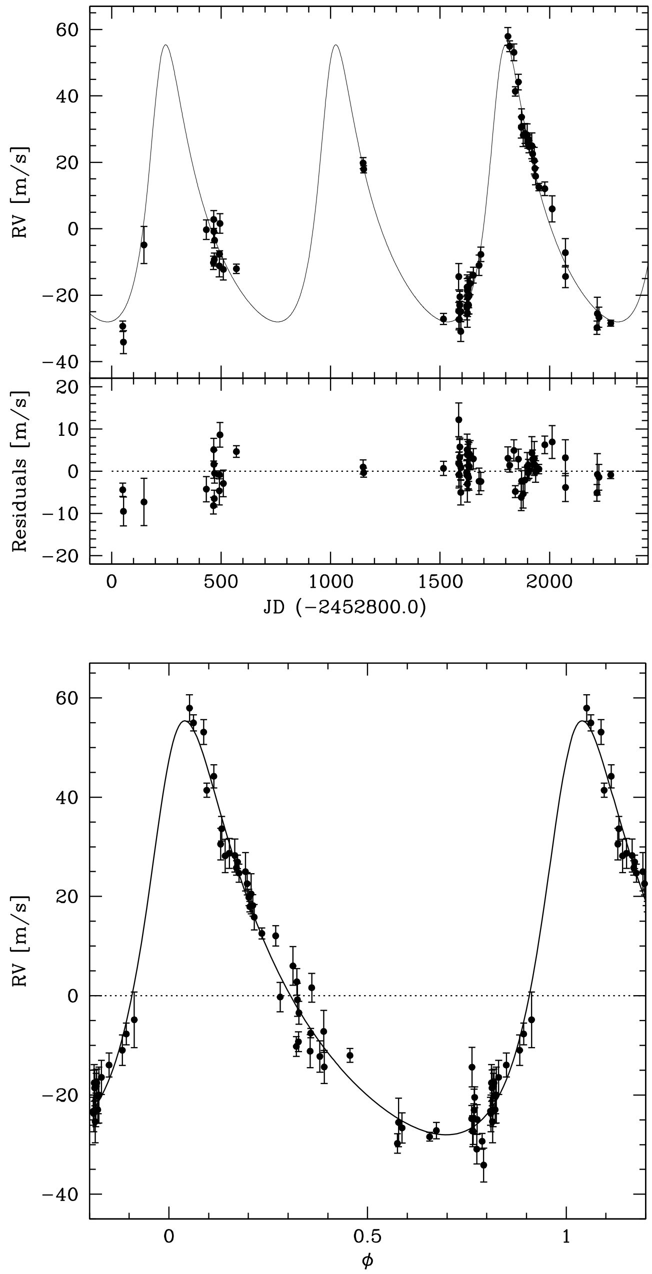

Fig. 1. *Top*: radial-velocity measurements of HD 5388 as a function of time, and the best Keplerian fit to the data with a period of 777-days, eccentricity of 0.40, and semi-amplitude of 42 m s^{-1}. The residuals of the fit are shown in the lower box. *Bottom*: phase-folded radial-velocity measurements of HD 5388, and the best Keplerian fit.

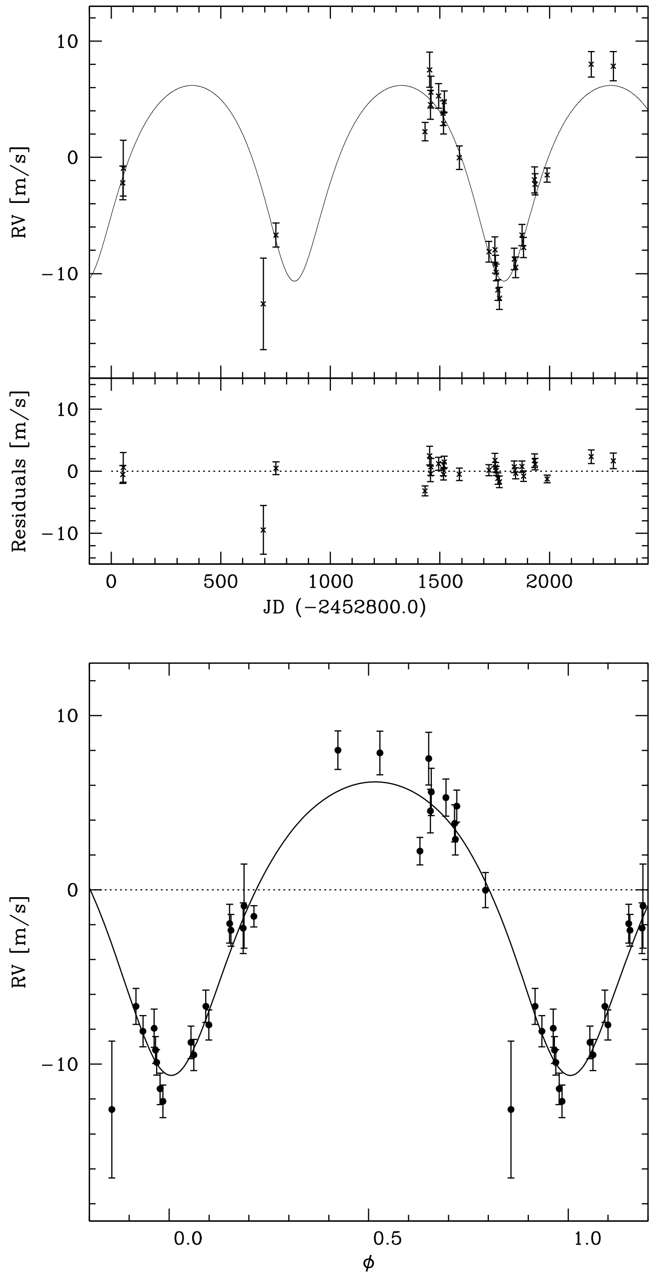

Fig. 2. *Top*: radial-velocity measurements of HD 181720 as a function of time, and the best Keplerian fit to the data with a period of 956-days, eccentricity of 0.26, and semi-amplitude of 8.4 m s^{-1}. The residuals of the fit are shown in the lower box. *Bottom*: phase-folded radial-velocity measurements of HD 181720, and the best Keplerian fit.

an amplitude 8.4 m s^{-1}. Given the mass for HD 181720, this signal can be explained by the presence of a 0.37 Jupiter-masses (minimum-mass) companion to HD 181720 (Table 2).

The residuals of the Keplerian fit (1.4 m s^{-1}) are slighly higher than the average error of the individual radial-velocity measurements (1.0 m s^{-1}). A visual inspection of the residuals (Fig. 2) suggests that some structure may exist in the data. However, the small number of points and the timeline of the measurements does not allow us to confirm this possibility.

The analysis of the bisector inverse slope shows that no clear correlation exists between the BIS and the radial-velocities (Fig. 4). Together with the low activity level of the star, we conclude that the 956-day orbital period observed can be better explained by the presence of a Saturn-like planet which orbits HD 181720.

4.3. HD 190984

From June 2004 to September 2009 we obtained a total of 47 radial-velocity measurements HD 190984 (Table 5). A look at the data (Fig. 3) shows a clear long period radial-velocity signal. Though a complete period is still not observable, the data can be well fitted with a Keplerian function with a period of 4885 days, an eccentricity of 0.57, and a semi-amplitude of 48 m/s. This

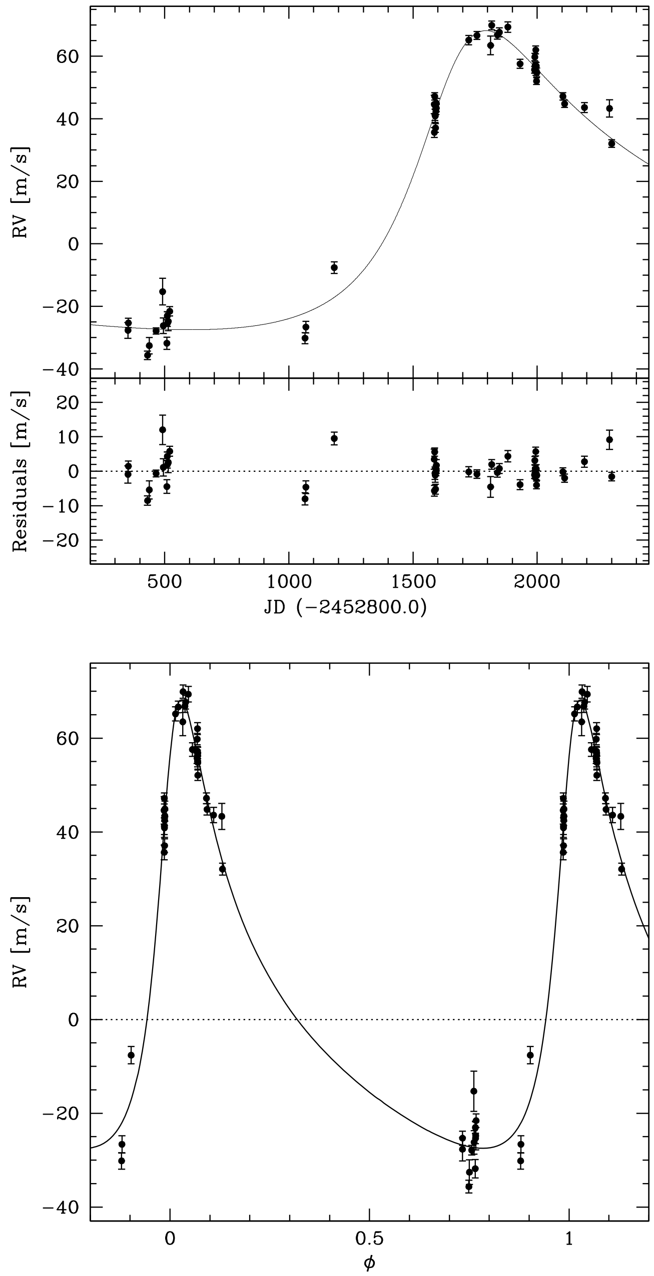

Fig. 3. *Top*: radial-velocity measurements of HD 190984 as a function of time, and the best Keplerian fit to the data with a period of 4885-days, eccentricity of 0.57, and semi-amplitude of 48 m s^{-1}. The residuals of the fit are shown in the lower box. *Bottom*: phase-folded radial-velocity measurements of HD 190984, and the best Keplerian fit.

signal is expected from a 3.1 Jupiter mass companion orbiting HD 190984.

The average photon noise error of the radial-velocities (1.7 m s^{-1}) is significantly below the observed residuals (3.44 m s^{-1}). Given the stellar projected rotational velocity, spectral type, and evolutionary stage together with the observing strategy used (see Sect. 2), this result is not unexpected. No correlation was found between BIS and the radial-velocities (Fig. 4). The observed radial-velocity signal is better explained as due to the presence of a long period giant planet orbiting HD 190984.

The fitted radial-velocity period is about twice as long as the baseline of our measurements. This increases the uncertainty of the orbital solution, as can be clearly seen in the error bars in Table 2. However, as preliminary as it can be, it seems very unlikely that the observed signal is not due to the presence of a giant planet in orbit about HD 190984. Since the HARPS program which included this star is now over, we cannot assure that a correct follow-up will be done over the next 5 years to better settle this result. We thus prefer to publish the present data, with a word of caution to say that the listed orbital parameters may be subject to some adjustments.

5. Concluding remarks

We present the detection of three new giant planets orbiting three moderately metal-poor stars from two separate HARPS GTO programs. This constitutes a strong addition to the previously known number of planets orbiting stars with metallicities significantly below solar.

Two of these stars (HD 181720 and HD 190984) were part of a dedicated program to search for giant planets orbiting a sample of ∼100 metal-deficient stars. Together with HD 171028 b (Santos et al. 2007), three planets have been discovered orbiting stars from this particular sample. In a very simplistic analysis, this suggests that at least 3% of stars with a metallicity below ∼−0.5 dex have giant planets. Such a result tends to confirm the hunch of Santos et al. (2004b) that the frequency distribution of giant planets as a function of stellar metallicity is rather flat for [Fe/H] values below solar. Interestingly, HD 171028, HD 181720, and HD 190984 all seem to be in the metal-rich tail of the metallicity distribution of the sample (see Santos et al. 2007, the former has a metallicity of −0.49 dex), which suggest that in this regime the frequency of planets is still an increasing function of the stellar metallicity (Fig. 5).

It is also curious to see that all the three planets discovered in this sample have long period orbits (above ∼1.5 years), as do all the remaining planet candidates discovered that orbit solar-type dwarfs with [Fe/H] significantly below solar. No hot-Jupiter was found in the HARPS "metal-poor" sample. The lack of short period planets in our metal-poor sample is also agrees with the results of the three-year long survey done by Sozzetti et al. (2009). In their sample of 160 metal-poor dwarfs, no planet was discovered, though some long period trends were found. We note however, that Sozzetti et al. would likely have missed some of the planets in our sample (e.g. HD 181720b, $P \sim 2.6$ years, $K = 8.4$ m s^{-1}) that induce RV semi-amplitudes smaller than the typical precision of their measurements (∼10 m s^{-1}).

A debate exists of whether there is a dependence between stellar metallicity and the orbital period of the discovered planets (see discussion in Santos et al. 2006). Our results support this tendency. We note however, that a few short period transiting hot Jupiters have been found which orbit metal-poor stars (see table in Ammler-von Eiff et al. 2009).

These results may have important implications for the models of planet formation and evolution. A relatively high frequency of planets orbiting metal-poor stars (in this case in long period orbits) could imply that the disk instability model is at play at these low [Fe/H] values. Planet formation through disk instability is relatively insensitive to the metallicity of the disk (and of the host star). An increase in the number of known giant planets orbiting low metallicity stars is crucial to settle these issues.

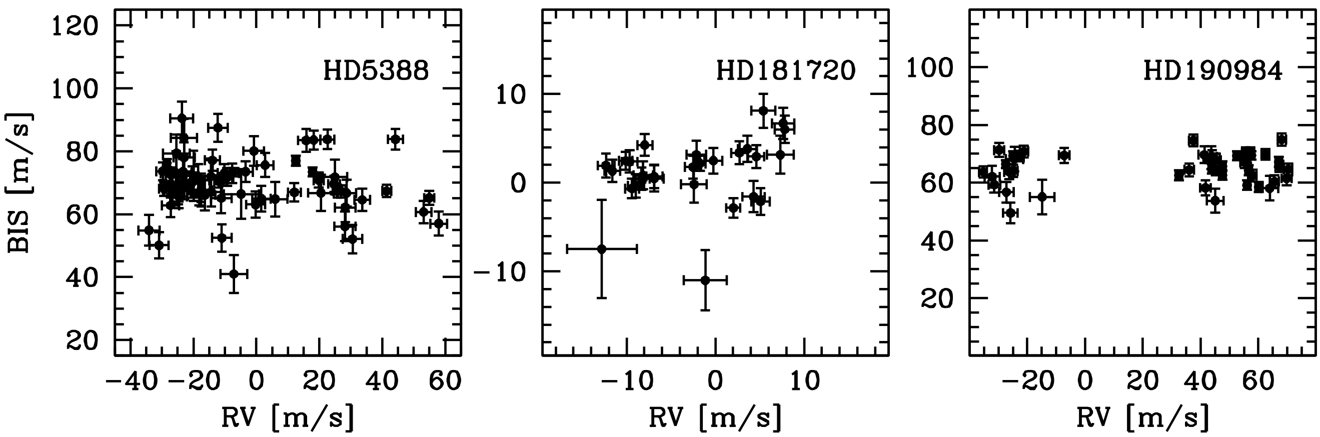

Fig. 4. Bisector inverse slope (BIS) as a function of radial-velocity for the three stars. The x and y scales were set the same for comparison purposes.

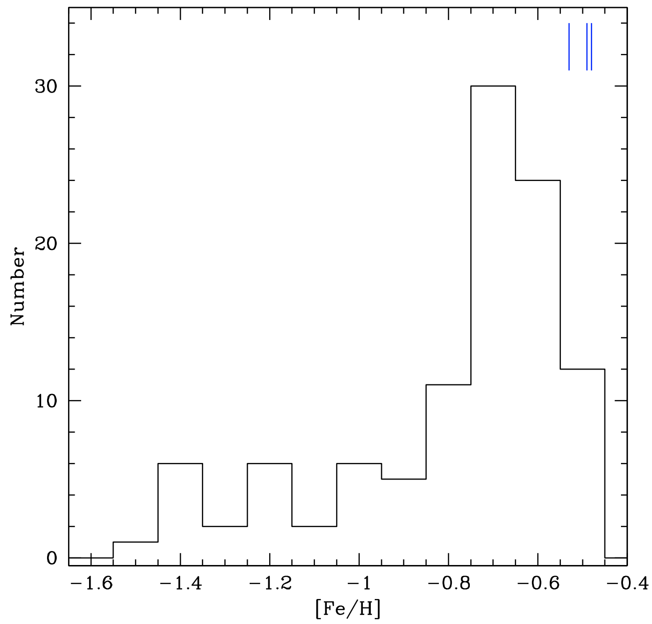

Fig. 5. Metallicity distribution for the whole HARPS "metal-poor" sample. The three vertical lines denote the [Fe/H] of the three stars in this sample for which a planet has been detected.

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