

# The HARPS search for southern extra-solar planets<sup>★,★★</sup>

## XV. Six long-period giant planets around BD -17 0063, HD 20868, HD 73267, HD 131664, HD 145377, and HD 153950

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### ABSTRACT

We report the discovery of six new substellar companions of main-sequence stars, detected by multiple Doppler measurements with the instrument HARPS installed on the ESO 3.6 m telescope, La Silla, Chile. These extrasolar planets orbit the stars BD -17 0063, HD 20868, HD 73267, HD 131664, HD 145377, and HD 153950. The orbital characteristics that reproduce the observed data are presented, as well as the stellar and planetary parameters. Masses of the companions range from 2 to 18 Jupiter masses, and periods range from 100 to 2000 days. The observational data are carefully analysed for activity-induced effects, and we conclude that the observed radial velocity variations are of exoplanetary origin. Of particular interest is the very massive planet (or brown-dwarf companion) orbiting the metal-rich HD 131664 with  $m_2 \sin i = 18.15 M_{\text{Jup}}$  and a 5.34-year orbital period. These new discoveries are consistent with the observed statistical properties of exoplanet samples known so far.

**Key words.** stars: planetary systems – techniques: radial velocities – techniques: spectroscopic – stars: general

## 1. Introduction

The HARPS<sup>1</sup> instrument (Pepe et al. 2003; Mayor et al. 2003) has been in operation since October 2003 on the 3.6 m telescope in La Silla Observatory, ESO, Chile. It has enabled the discovery of several tens of extrasolar systems, including very low-mass companions (e.g., Mayor et al. 2009). In the context of the Guaranteed Time Observation program, the strategy of HARPS observations is adapted to different target samples. High-precision is achieved for a sub-sample of bright stars, known to be stable at a high level. In addition, a larger, volume-limited sample of stars are being explored at moderate precision (superior to  $3 \text{ m s}^{-1}$  or signal-to-noise ratio of 40) to complete our view of exoplanets' properties with extended statistics. The HARPS sample completes the CORALIE sample with stars from 50 to 57.5 pc distance, and together, these samples contain about 2500 stars. The results presented in this paper concern this wide exploratory program of moderate precision. Earlier findings for this stellar sample were provided for 8 giant planets, in

Pepe et al. (2004), Moutou et al. (2005), Lo Curto et al. (2006), and Naef et al. (2007). The statistical properties of these planets agree well with those described in the literature (Marcy et al. 2005; Udry & Santos 2007), regarding the frequency of planets and the distribution of their parameters.

We report the discovery of six new planets in the volume-limited sample of main-sequence stars, using multiple HARPS Doppler measurements over 3 to 5 years. They are massive and long-period planets. Section 2 describes the characteristics of the parent stars, and Sect. 3 presents the Doppler measurements and discusses the planetary orbital solutions.

## 2. Characteristics of the host stars

The host stars discussed here are BD -17 0063, HD 20868, HD 73267, HD 131664, HD 145377, and HD 153950. We used the  $V$  magnitude and  $B - V$  color index given in the HIPPARCOS catalog (ESA 1997), and the Hipparcos parallaxes  $\pi$  as reviewed by van Leeuwen (2007), to estimate the absolute magnitude  $M_V$ . The bolometric correction of Flower (1996) was then applied to recover the absolute luminosity of the stars.

Spectroscopic parameters  $T_{\text{eff}}$ ,  $\log g$ , and  $[\text{Fe}/\text{H}]$  were derived from a set of FeI and FeII lines (Santos et al. 2004) for which equivalent widths were derived with ARES (Automatic Routine for line Equivalent width in stellar Spectra; Sousa et al. 2007, 2008) in the HARPS spectra. The error bars reflect the

<sup>★</sup> Based on observations made with the HARPS instrument on the ESO 3.6 m telescope at La Silla Observatory under programme ID 072.C-0488(E).

<sup>★★</sup> Tables 3–8 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/496/513>

<sup>1</sup> High-Accuracy Radial-velocity Planet Searcher.

**Table 1.** Observed and inferred stellar parameters for the planet-hosting stars presented in this paper.

Parameter	BD-17 0063	HD 20868	HD 73267	HD 131664	HD 145377	HD 153950	
Sp	K5V	K3/4IV	G5V	G3V	G3V	F8V	
$V$	[mag]	9.62	9.92	8.90	8.13	8.12	7.39
$B - V$	[mag]	1.128	1.037	0.806	0.667	0.623	0.565
$\pi$	[mas]	28.91 (1.27)	20.42 (1.38)	18.21 (0.93)	18.04 (0.73)	18.27 (0.94)	20.16 (0.70)
$d$	[pc]	34.6 (1.5)	48.9 (3.5)	54.91 (3.0)	55.43 (2.3)	57.7 (3.0)	49.6 (1.8)
$M_V$	[mag]	6.92	6.47	5.20	4.41	4.31	3.91
$B.C.$	[mag]	-0.49	-0.41	-0.195	-0.08	-0.055	-0.038
$L$	[ $L_\odot$ ]	0.21 (0.02)	0.296 (0.04)	0.783 (0.09)	1.46 (0.13)	1.56 (0.17)	2.22 (0.17)
$T_{\text{eff}}$	[K]	4714 (93)	4795 (124)	5317 (34)	5886 (21)	6046 (15)	6076 (13)
$\log g$	[cgs]	4.26 (0.24)	4.22 (0.26)	4.28 (0.1)	4.44 (0.1)	4.49 (0.1)	4.37 (0.1)
[Fe/H]	[dex]	-0.03 (0.06)	0.04 (0.1)	0.03 (0.02)	0.32 (0.02)	0.12 (0.01)	-0.01 (0.01)
$M_*$	[ $M_\odot$ ]	0.74 (0.03)	0.78 (0.03)	0.89 (0.03)	1.10 (0.03)	1.12 (0.03)	1.12 (0.03)
$v \sin i$	[km s $^{-1}$ ]	1.5	1.1	1.65	2.9	3.85	3.0
$\log R'_{\text{HK}}$		-4.79 (0.1)	-4.99 (0.1)	-4.97 (0.07)	-4.82 (0.07)	-4.68 (0.04)	-4.89 (0.03)
$P_{\text{rot}}(HK)^a$	[days]	39	51	42	22	12	14
Age	[Gyr]	4.3 (4)	4.5 (4)	7.4 (4.5)	2.4 (1.8)	1.3 (1)	4.3 (1)
$R_*$	[ $R_\odot$ ]	0.69	0.79	1.04	1.16	1.14	1.34

<sup>a</sup> The rotation periods of the stars are not derived from observations, but indirectly inferred from  $\log R'_{\text{HK}}$  with relationships in Mamajek & Hillenbrand (2008) and Noyes et al. (1984).

large number of FeI and FeII lines used, and a good precision was obtained, especially for the effective temperature. For gravity and metallicity estimates, we are limited by systematics, which are included in the error bars.

We finally estimated the stellar mass and age, from  $T_{\text{eff}}$ , [Fe/H], and parallax estimates, by using the Padova models of Girardi et al. (2000) and its web interface as described in da Silva et al. (2006). Errors were propagated and estimated using a Bayesian method. The stellar radius was finally estimated from the simple relationship between luminosity, temperature, and radius.

From the HARPS cross-correlation function, we were able to derive an estimate of the projected rotational velocity of the star,  $v \sin i$ . The measurement of the core reversal in the calcium H & K lines provides an estimate of the chromospheric activity  $\log R'_{\text{HK}}$  (method described by Santos et al. 2000). The error bars of this quantity include the scatter as well as some systematics; these are particularly large for the faintest and coolest stars, with typical signal-to-noise ratios of 10 in the region of the calcium doublet. All measured stellar parameters and their errors are given in Table 1. A short presentation of the host stars follows.

### 2.1. BD-17 0063, HD 20868, and HD 73267: three quiet K-G stars

BD-17 0063 is a main-sequence K5 star, and HD 20868 is a slightly evolved K3/4 IV star. Both are slow rotators that do not exhibit significant activity jitter. They have a metallicity similar to the Sun, masses of  $0.74 M_\odot$  and  $0.78 M_\odot$  respectively, and estimated ages of more than 4 Gyr. HD 73267 is more massive with  $0.89 M_\odot$ . It also shows no significant activity, rotates slowly and has a solar metallicity. It is a 7 Gyr-old G5 dwarf. The rotation period of our sample stars could be inferred from the activity level using the relations of Noyes et al. (1984) (colour to convection turnover time relations) and Mamajek & Hillenbrand (2008) (Rossby number to  $\log R'_{\text{HK}}$  relations). We derive rotation periods of 39, 51, and 42 days, for BD-17 0063, HD 20868, and HD 73267, respectively.

### 2.2. HD 131664, HD 145377, and HD 153950: two early G and one late F dwarf stars

The other three stars HD 131664, HD 145377, and HD 153950 are slightly more massive than the Sun with masses of 1.10, 1.12 and  $1.12 M_\odot$ , respectively. HD 145377 is the most active star and its age was estimated around 1 Gyr. Their rotational periods are also shorter than for the first group of lower mass stars, to be approximately 22, 12 and 14 days for HD 131664, HD 145377, and HD 153950, respectively. HD 131664 and HD 145377 are both metal-rich stars with [Fe/H] = 0.32 and 0.12, respectively, while HD 153950 has a metallicity close to solar.

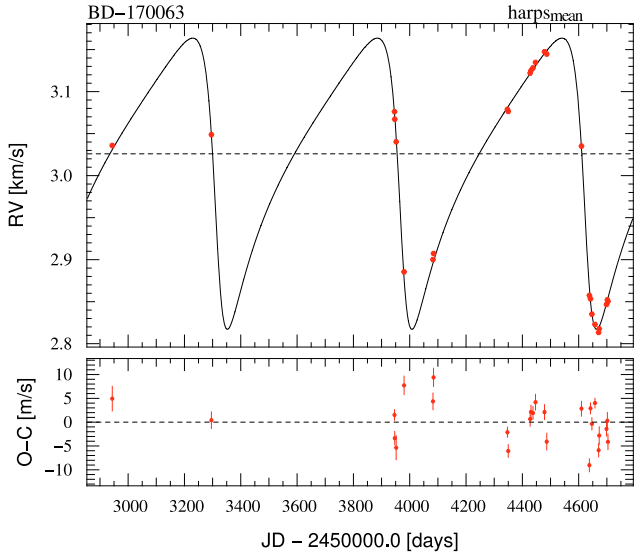
## 3. Radial velocity data and orbital solutions

### 3.1. BD-17 0063

We gathered 26 spectra of BD-17 0063 with HARPS over a timespan of 1760 days between 2003 October 31 and 2008 July 5. The mean radial velocity uncertainty is  $1.6 \text{ m s}^{-1}$ . The measurements are given in Table 3 (electronic version only) and shown in Fig. 1. We fitted a Keplerian orbit to the observed radial velocity variations, and found a best-fit solution at a period of 655.6 days. It is an eccentric orbit ( $e = 0.54$ ) with a semi-amplitude of  $173 \text{ m s}^{-1}$ . The reduced  $\chi^2$  derived for this fit was 3.2.

The inverse bisector slope was estimated from the cross-correlation function and its time series was also examined, to exclude stellar variability as the origin for the observed radial velocity variation (Queloz et al. 2001). The error in the bisector slope is assumed to be twice the error in the velocity, conservatively. No correlation is found between the bisector slope and the velocity, which excludes a blend scenario. The bisector values for BD-17 0063 are consistent with a constant value with a standard deviation of  $7 \text{ m s}^{-1}$ , over the 4.8 yr time span. With the long rotation period estimated for the star (39 days), a radial velocity modulation related to spot activity is also improbable. These activity indicators therefore strongly support the planetary origin of the observed signal.

Using the stellar parameters determined in the previous section, we infer a minimum planetary mass of  $m_2 \sin i = 5.1 M_{\text{Jup}}$  and semi-major axis of 1.34 AU. The periastron distance is

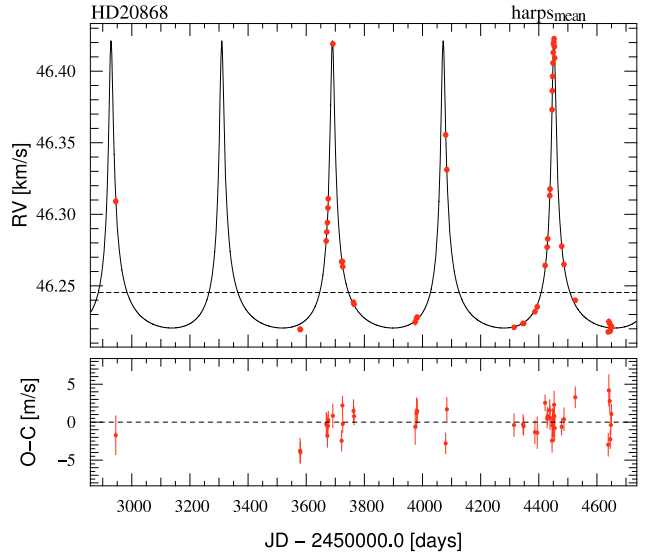


**Fig. 1.** The radial-velocity curve of BD-17 0063 obtained with HARPS. *Top*: individual radial-velocity measurements (dots) versus time, and fitted orbital solution (solid curve); *Middle*: residuals to the fitted orbit versus time; *Bottom*: radial-velocity measurements with phase-folding, using the period of 655.6 days and other orbital parameters as listed in Table 2. A  $5.1 M_{\text{Jup}}$  companion to this K5 dwarf is evidenced.

0.87 AU which infers a transit probability of only 0.4%. No attempt has yet been made to monitor the photometric light curve of BD-17 0063, nor to search for a potential transit. Figure 1 shows the radial velocity signal folded with the planetary phase, and the residuals with time, after subtraction of the main signal. There is no significant periodic trend nor linear drift in the O–C residuals, with a standard deviation of  $4.1 \text{ m s}^{-1}$ , i.e. marginally above the individual errors. All parameters of the orbit and the planet are given in Table 2 with their estimated error.

### 3.2. HD 20868

Our observations of HD 20868, obtained over 1705 days between 2003 November 1 and 2008 July 2, have provided 48 HARPS measurements. The mean uncertainty in the radial velocity measurements is  $1.5 \text{ m s}^{-1}$ . The measurements are given in Table 4 (electronic version only). Figure 2 shows the velocities as a function of time, as well as the Keplerian orbit with a period of 380.85 days that provides the best fit function of the data. The residual values, after subtraction of the fit, are also shown as a function of time. There is no significant trend in these



**Fig. 2.** The radial-velocity curve of HD 20868 obtained with HARPS. *Top*: individual radial-velocity measurements (dots) versus time, and fitted orbital solution (solid curve); *Middle*: residuals to the fitted orbit versus time; *Bottom*: radial-velocity measurements with phase-folding, using the period of 380.85 days and other orbital parameters as listed in Table 2. The K3/4 IV star has a  $1.99 M_{\text{Jup}}$  companion.

residuals, characterized by a standard deviation of  $1.7 \text{ m s}^{-1}$ . The reduced  $\chi^2$  for this fit is 1.27.

The best-fit orbital solution is a strongly eccentric orbit ( $e = 0.75$ ) with a semi-amplitude of  $100.34 \text{ m s}^{-1}$ . The inferred minimum mass of the companion responsible for this velocity variation is  $1.99 M_{\text{Jup}}$ , and a semi-major axis of 0.947 AU is then derived from the third Kepler law. The periastron distance is 0.54 AU, which corresponds to a transit probability of 0.7%.

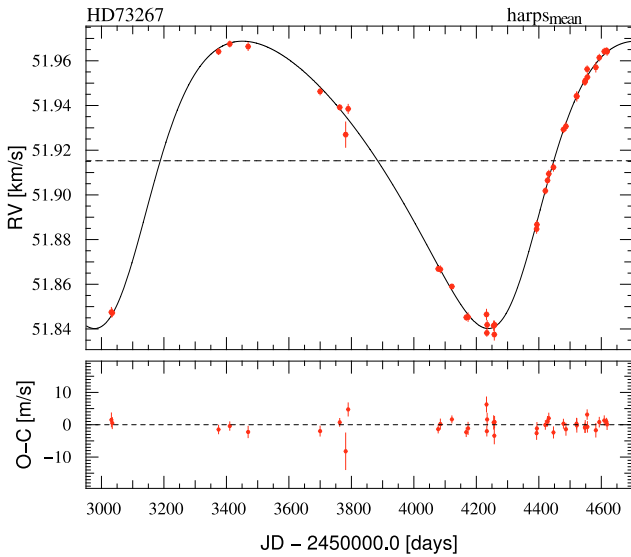
The bisector test was applied and excludes velocity variations due to stellar activity, a trend which is confirmed by the long rotation period.

### 3.3. HD 73267

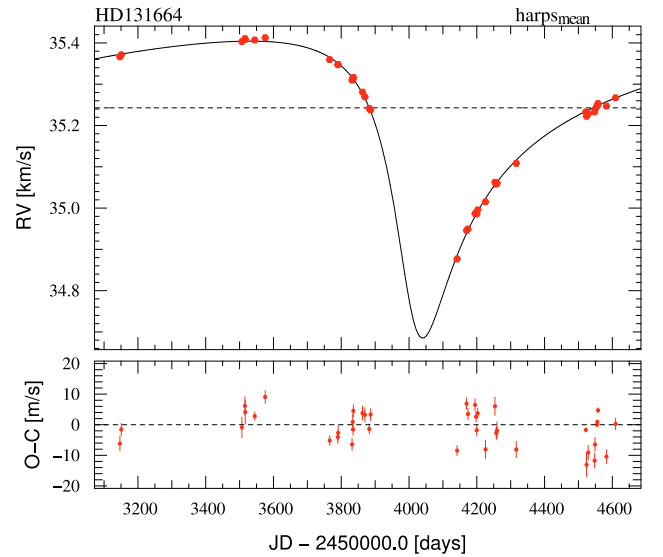
We gathered 39 HARPS measurements of HD 73267 over a time span of 1586 days, between 2004 November 27 and 2008 May 31. Small individual uncertainties were derived of a mean value  $1.8 \text{ m s}^{-1}$ . Data are shown in Table 8 and in Fig. 3. The observed velocity variations were reproduced by a Keplerian orbit. The best-fit solution corresponds to a period of 1260 days, eccentricity of 0.256, and semi-amplitude

**Table 2.** Orbital and physical parameters for the planets presented in this paper.  $T$  is the epoch of periastron.  $\sigma(\text{O-C})$  is the residual noise after orbital fitting of the combined set of measurements.  $\chi^2_{\text{red}}$  is the reduced  $\chi^2$  of the fit.

Parameter		BD-17 0063 b	HD 20868 b	HD 73267 b	HD 131664 b	HD 145377 b	HD 153950 b
$P$	[days]	655.6 (0.6)	380.85 (0.09)	1260. (7)	1951. (41)	103.95 (0.13)	499.4 (3.6)
$T$	[JD-2 400 000]	54 627.1 (1.5)	54 451.52 (0.1)	51 821.7 (16)	52 060. (41)	54 635.4 (0.6)	54 502. (4.3)
$e$		0.54 (0.005)	0.75 (0.002)	0.256 (0.009)	0.638 (0.02)	0.307 (0.017)	0.34 (0.021)
$\gamma$	[km s <sup>-1</sup> ]	3.026 (0.0012)	46.245 (0.0003)	51.915 (0.0005)	35.243 (0.004)	11.650 (0.003)	33.230 (0.001)
$\omega$	[deg]	112.2 (1.9)	356.2 (0.4)	229.1 (1.8)	149.7 (1.0)	138.1 (2.8)	308.2 (2.4)
$K$	[m s <sup>-1</sup> ]	173.3 (1.7)	100.34 (0.42)	64.29 (0.48)	359.5 (22.3)	242.7 (4.6)	69.15 (1.2)
$a_1 \sin i$	[10 <sup>-3</sup> AU]	8.76	2.305	7.196	49.678	2.2074	2.981
$f(m)$	[10 <sup>-9</sup> M <sub>⊙</sub> ]	209.0	11.26	31.324	4295.665	132.788	14.174
$m_2 \sin i$	[M <sub>Jup</sub> ]	5.1 (0.12)	1.99 (0.05)	3.06 (0.07)	18.15 (0.35)	5.76 (0.10)	2.73 (0.05)
$a$	[AU]	1.34 (0.02)	0.947 (0.012)	2.198 (0.025)	3.17 (0.03)	0.45 (0.004)	1.28 (0.01)
$N_{\text{meas}}$		26	48	39	41	64	49
$\text{Span}$	[days]	1760	1705	1586	1463	1106	1791
$\sigma(\text{O-C})$	[m s <sup>-1</sup> ]	4.1	1.7	1.7	4.0	15.3	3.9
$\chi^2_{\text{red}}$		3.2	1.27	1.19	2.97	10.13	2.40



**Fig. 3.** The radial-velocity curve of HD 73267 obtained with HARPS. *Top*: individual radial-velocity measurements (dots) versus time, and fitted orbital solution (solid curve). The star has a companion of minimum mass  $3.06 M_{\text{Jup}}$  and orbital period 1260 days. *Bottom*: residual to the fitted orbit versus time.



**Fig. 4.** The radial-velocity curve of HD 131664 obtained with HARPS. *Top*: individual radial-velocity measurements (dots) versus time, and fitted orbital solution (solid curve). It shows a very massive planetary companion of  $m_2 \sin i = 18.15 M_{\text{Jup}}$  with an orbital period of 1951 days. *Bottom*: residual to the fitted orbit versus time.

of  $64.29 \text{ m s}^{-1}$ . The scatter in the residuals was consistent with the radial velocity uncertainty, and these residuals do not show any significant trend. The O-C standard deviation was  $1.7 \text{ m s}^{-1}$ , and the reduced  $\chi^2$  was evaluated to be 1.19.

The bisector variations were neither correlated with the velocity variations, nor in phase with the signal, which excludes stellar variability as being their cause. The estimated rotation period of the star was again long, and spot-related activity cannot be considered as a potential origin for the observed signal.

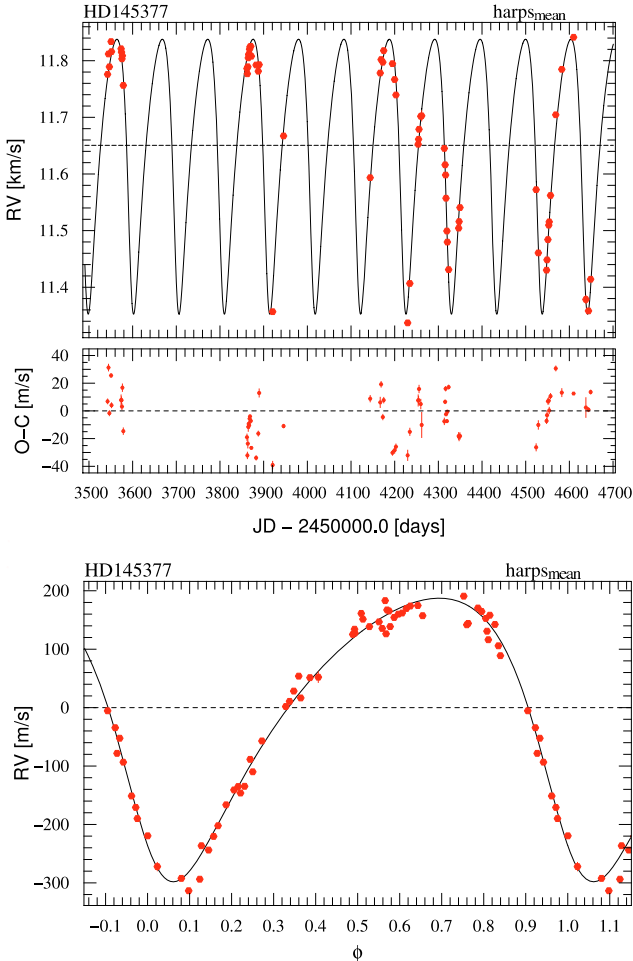
The minimum mass of the inferred companion was  $3.06 M_{\text{Jup}}$ , and a semi-major axis of 2.198 AU was calculated for this 3.44 year period companion.

### 3.4. HD 131664

We gathered 41 measurements of HD 131664 over 1463 days with HARPS, between 2004 May 21 and 2008 May 23. Individual uncertainties have a mean value of  $2 \text{ m s}^{-1}$ . A

long-term velocity variation is observed (Fig. 4), which has a best fit solution of a Keplerian orbit of 1951 days, 0.638 eccentricity, and a large semi-amplitude  $K$  of  $359.5 \text{ m s}^{-1}$ . The residuals after subtraction of this signal have a standard deviation of only  $4 \text{ m s}^{-1}$  and no specific trend. The reduced  $\chi^2$  statistic for the fit is 2.97. Although the orbital fit to the data appears robust, the time coverage of this planetary orbit is discontinuous, since most of the periastron passage was unfortunately not observed. This limits the precision we can achieve for the orbital parameters.

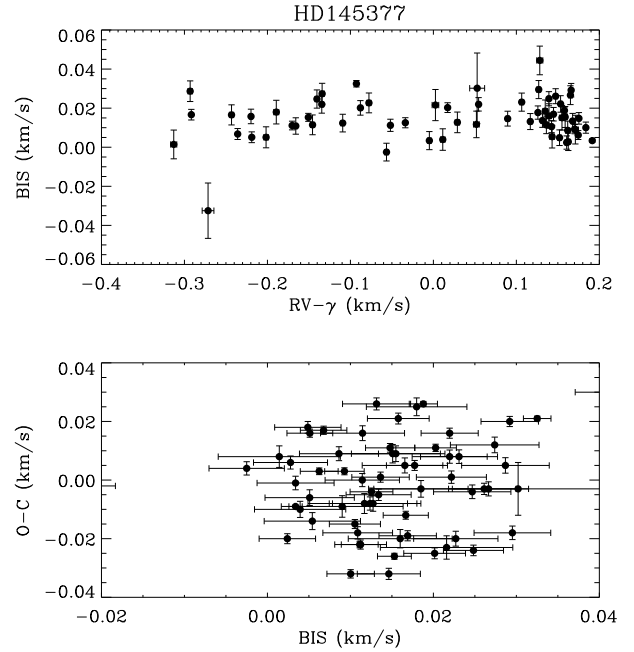
The bisector test again confirms that the origin of this signal is due to a sub-stellar companion. Despite the long period of the signal, the large amplitude infers a large projected mass of the companion, i.e.  $m_2 \sin i = 18.15 M_{\text{Jup}}$ . This massive planet, or brown-dwarf companion, orbits the parent star at a semi-major axis of 3.17 AU.



**Fig. 5.** The radial-velocity curve of HD 145377 obtained with HARPS. *Top*: individual radial-velocity measurements (dots) versus time, and fitted orbital solution (solid curve); *Middle*: residuals to the fitted orbit versus time; *Bottom*: radial-velocity measurements with phase-folding, using the period of 103.95 days and other orbital parameters as listed in Table 2. The residual jitter is due to stellar variability (expected from activity indicators) and shows no periodic trend. A planet of minimum mass  $5.76 M_{\text{Jup}}$  is evidenced.

### 3.5. HD 145377

We gathered 64 measurements of HD 145377 with HARPS between 2005 June 21 and 2008 July 1, over 1106 days, with a mean uncertainty of  $2.3 \text{ m s}^{-1}$ . A relatively large amplitude velocity variation is observed, as shown in Fig. 5. Its best-fit function has a 103.95 day period. The orbit is eccentric ( $e = 0.307$ ) with semi-amplitude  $K = 242.7 \text{ m s}^{-1}$ . Although the signal is clear and stable over more than 10 periods, the residuals to the fit are affected by an additional jitter, of amplitude  $15.3 \text{ m s}^{-1}$ . This jitter was expected from the relatively young age (1 Gyr) and the high value of  $\log R'_{\text{HK}}$  (mean value is  $-4.68$ ), which strongly suggests that stellar variability is being observed in addition to the main signal. The O–C residuals do not, however, exhibit a periodicity related to the 12 d rotation, which is unsurprising for about 80 rotation cycles of the star. The Lomb-Scargle periodogram of the residuals do, however, show a tendency for a curved drift that could be indicative of a second, longer-period planet, and other periodic signals could be present but are too weak to be significant. When taken into account, the curved drift



**Fig. 6.** The inverse bisector slope is plotted against the radial velocity of HD 145377 (*top*) and against the residuals to the fitted orbit (*bottom*). No correlation between these quantities is observed. Although the bisector varies in a similar scale as the fit residuals, we cannot correct for spot-related activity. The amplitude of bisectors' variations still remains small compared to the range of radial velocities.

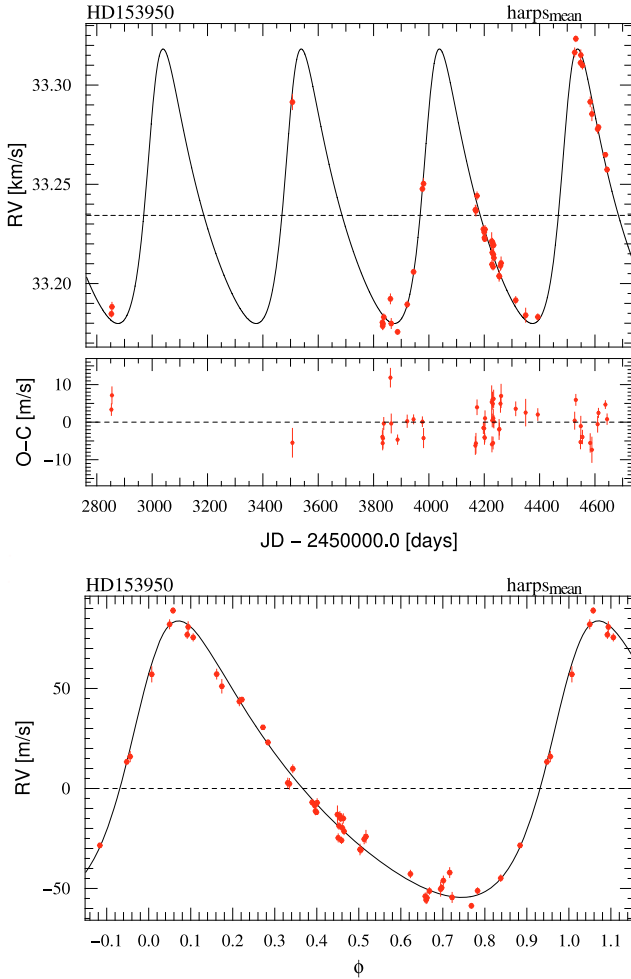
decreases the residual noise from 15 to about  $10 \text{ m s}^{-1}$ . More data in the future may therefore reveal more planets in this system, but the present material is inconclusive in this respect.

Figure 6 shows the bisector behaviour with respect to radial velocity (top) and as a function of the fit residuals. The scatter of the bisector span is larger than for the other stars, with a value of  $11 \text{ m s}^{-1}$ , and it confirms that we see some line profile variations with time. The bisector slope does not, however, correlate with the radial velocity, excluding stellar variability as the only origin of the observed velocity variation. We also find no correlation between the residuals to the fitted orbit and the bisector span (Fig. 6 bottom). Such a correlation, observed when the activity is mainly related to spots, could have been used to correct the radial velocities for stellar variability, as explained in Melo et al. (2007). Finally, as a test of the origin of the RV jitter, we observed HD 145377 in a sequence of 10 consecutive 90 s exposures, for which a standard deviation of  $2.5 \text{ m s}^{-1}$  is derived. The stellar jitter therefore does not originate in short-term acoustic modes but rather from chromospheric activity features.

The planetary companion of HD 145377 is a  $m_2 \sin i = 5.76 M_{\text{Jup}}$  planet orbiting with a 103.95 d period. The semi-major axis is 0.45 AU. The periastron distance is 0.34 AU, which corresponds to a transit probability of 0.14%.

### 3.6. HD 153950

Finally, the star HD 153950 was observed 49 times with HARPS between 2003 August 1 to 2008 June 26 (a 1791 day timespan). The mean uncertainty in the velocity measurements is  $2 \text{ m s}^{-1}$ . The velocity variation with time is well described by a Keplerian orbit of 499.4 day period (Fig. 7). It is again an eccentric orbit with  $e = 0.34$  and a semi-amplitude of  $69.15 \text{ m s}^{-1}$ . The bisector is rather flat over time, and correlates neither with the orbital phase, nor the position of the velocity peak. The residuals around



**Fig. 7.** The radial-velocity curve of HD 153950 obtained with HARPS. *Top*: individual radial-velocity measurements (dots) versus time, and fitted orbital solution (solid curve); *Middle*: residuals to the fitted orbit versus time; *Bottom*: radial-velocity measurements with phase-folding, using the period of 499.4 days and other orbital parameters as listed in Table 2. The planetary companion has a minimum mass of  $2.73 M_{\text{Jup}}$ .

the best solution have a standard deviation of  $4 \text{ m s}^{-1}$ , and the reduced  $\chi^2$  statistic obtained for the fit is 2.40.

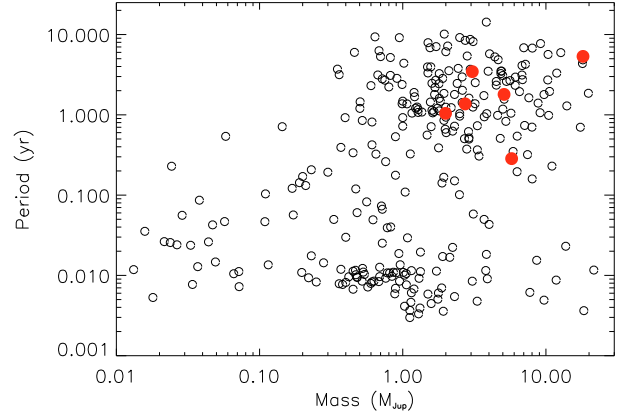
This radial velocity curve therefore implies that there is a planetary companion of minimum mass  $2.73 M_{\text{Jup}}$ , and semi-major axis 1.28 AU.

The orbit and planetary parameters of the six new systems described above are given with their inferred errors in Table 2.

#### 4. Conclusion

From long-term observations with HARPS of individual uncertainty about  $2 \text{ m s}^{-1}$ , we have been able to infer the presence of 6 new substellar companions around the main-sequence stars BD-17 0063, HD 20868, HD 73267, HD 131664, HD 145377, and HD 153950.

The analysis of the HARPS cross-correlation function and, in particular, the bisector span of each measurement, has allowed us to reject long-term stellar variability as the origin of the observed radial-velocity curve, even for the most active star, HD 145377. The characterization of the planetary companion is not significantly sensitive to the stellar variability, because of



**Fig. 8.** The present mass-period diagram of known exoplanets (open circles) showing the location of the six new planets presented in this paper (filled circles). They belong to the bulge of the most massive, longest period bodies.

the planet's relatively short period with respect to our long time span of observations (104 versus 1106 days). The stellar activity translates into a residual jitter that does not obscure the planet's signal.

The planet orbiting HD 131664 is extremely massive with a minimum mass of  $18.15 M_{\text{Jup}}$ , which is over the deuterium limit. Its characteristics are similar to those of the other massive planet in a distant orbit HD 168443 c (Udry et al. 2002), although no internal planet to the system of HD 131664 has been discovered so far. The period of HD 131664 b (1951 days or 5.34 years) is also among the dozen longest periods known so far. Depending on the true system age of HD 131664, the magnitude difference with the parent star could be as low as 13.5 in the  $K$  band – for the lower edge of the age range – and up to 20, using the models of Baraffe et al. (2002) for luminosity estimates. The angular separation ranges from 0.035 to 0.16 arcsec during the orbit. Depending on the system's inclination – and thus the true mass of the companion – it may be a target for future direct imaging investigations, which would enable a more robust characterisation to be completed for this unusual system. We note also that the parent star is particularly metal-rich ( $[\text{Fe}/\text{H}] = 0.32$ ) in comparison with the mean metallicity of the solar neighbourhood. The rare combination of parameters for this system – companion mass, orbital period, star metallicity – could provide important constraints for theories of planetary formation. Deriving astrometric measurements of the six new systems with VLTI/PRIMA would be invaluable in constraining their true mass.

The new planets discussed in this paper are part of a large number of long period, massive extrasolar planets in eccentric orbits, with masses in the range  $2\text{--}6 M_{\text{Jup}}$  and periods of 0.3 to 5.3 years. Their properties can be discussed in the framework of the statistical studies performed in well-defined stellar samples, such as the ELODIE, CORALIE, or Lick+Keck+AAT surveys (see Marcy et al. 2005 and Udry & Santos 2007, for in-depth discussions):

- Giant gaseous planets are found around about 6–7% of known main-sequence stars, with semi-major axes of up to about 5 AU. These six new planets contribute to increase the number of known systems, presently consisting in 15 planets orbiting 850 stars in the volume-limited sample monitored by HARPS. The 1.8% frequency of planet occurrence in this sample for which observations started in 2003, is, however, not yet at the level of the oldest surveys. Identically, only five

hot Jupiters were discovered in our sample, representing a frequency of 0.6%, to be compared with the 1.2% frequency for more complete surveys. The new planet sample presented in this paper still contains the longest periods found in this specific survey, measurements having been derived during the earliest stages of HARPS operations (Fig. 8).

- The distribution of planet masses currently favours small masses, despite the strong observational bias towards massive planets. We have presented new evidence of planets in the highest mass end, with minimum masses of 2 to 18  $M_{\text{Jup}}$  (Fig. 8).
- The period and eccentricity properties of the six new planets confirm the global tendency of significant dispersion in eccentricities beyond the circularization zone due to tidal interactions, compared with the circular orbits of giant and distant planets in the Solar System. The origin of this dispersion in eccentricities remains a mystery, despite a number of theoretical attempts to reproduce the observed distribution using a variety of eccentricity-damping physical processes.
- Host stars of systems with giant gaseous planets are significantly more metal-rich than average (Santos et al. 2005; Fischer & Valenti 2005), which is not inconsistent with the new exoplanet sample data set presented here, with two stars having excess metallicity compared with the Sun and there being no metal-poor planet-host star.
- About 12% of systems with gaseous giant planets are multiple. We found no indication of a second body in any of the new systems, with a very small scatter of the residuals of the order of a few  $\text{m s}^{-1}$  (except for HD 145377, which is active). To find planets of lower mass in these systems, a high-precision strategy should now be developed. Finding larger distance planets in these systems is also possible, although no significant long-term drift has yet been observed.
- Finally, the mass-period distribution of the six new planets corroborates with the more general properties that more massive planets have longer orbital distances (e.g. Udry & Santos 2007).

Adding new extrasolar systems to the  $\sim 300$  planets known to date is of course of significant importance in characterizing their properties. Radial velocity survey, in addition to transit-search programs, experience the observational bias of detecting more easily the short-period and massive planets (the rarest ones),

which may be the reason why the signature of a giant planet has been found for only 6–7% of planets in the solar neighbourhood. We note that the proportion of stars with planetary systems significantly increases when planets in the mass range of Neptune or below are discovered (Mayor & Udry 2008). Extending the planet sample, especially in carefully selected volume-limited samples of main-sequence stars as monitored by HARPS, is an outstanding challenge of this scientific field, to help understanding the mechanisms that form and maintain planets orbiting around other stars.

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## References

- Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 2002, *A&A*, 382, 563  
 da Silva, L., Girardi, L., Pasquini, L., et al. 2006, *A&A*, 458, 609  
 ESA. 1997, *VizieR Online Data Catalog*, 1239, 0  
 Fischer, D. A., & Valenti, J. 2005, *ApJ*, 622, 1102  
 Flower, P. J. 1996, *ApJ*, 469, 355  
 Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, *A&AS*, 141, 371  
 Lo Curto, G., Mayor, M., Clausen, J. V., et al. 2006, *A&A*, 451, 345  
 Mamajek, E. E., & Hillenbrand, L. A. 2008, *ArXiv e-prints*  
 Marcy, G., Butler, R. P., Fischer, D., et al. 2005, *Progr. Theor. Phys. Suppl.*, 158, 24  
 Mayor, M., & Udry, S. 2008, in *Nobel Symposium proceedings T 130*, 014010  
 Mayor, M., Pepe, F., Queloz, D., et al. 2003, *The Messenger*, 114, 20  
 Mayor, M., Udry, S., Lovis, C., et al. 2009, *A&A*, 493, 639  
 Melo, C., Santos, N. C., Gieren, W., et al. 2007, *A&A*, 467, 721  
 Moutou, C., Mayor, M., Bouchy, F., et al. 2005, *A&A*, 439, 367  
 Naef, D., Mayor, M., Benz, W., et al. 2007, *A&A*, 470, 721  
 Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, *ApJ*, 279, 763  
 Pepe, F., Rupprecht, G., Avila, G., et al. 2003, in *SPIE*, 4841, 1045  
 Pepe, F., Mayor, M., Queloz, D., et al. 2004, *A&A*, 423, 385  
 Queloz, D., Henry, G. W., Sivan, J. P., et al. 2001, *A&A*, 379, 279  
 Santos, N. C., Mayor, M., Naef, D., et al. 2000, *A&A*, 361, 265  
 Santos, N. C., Israelian, G., & Mayor, M. 2004, *A&A*, 415, 1153  
 Santos, N. C., Israelian, G., Mayor, M., et al. 2005, *A&A*, 437, 1127  
 Sousa, S. G., Santos, N. C., Israelian, G., Mayor, M., & Monteiro, M. J. P. F. G. 2007, *A&A*, 469, 783  
 Sousa, S. G., Santos, N. C., Mayor, M., et al. 2008, *A&A*, 487, 373  
 Udry, S., & Santos, N. C. 2007, *ARA&A*, 45, 397  
 Udry, S., Mayor, M., Naef, D., et al. 2002, *A&A*, 390, 267  
 van Leeuwen, F. 2007, *A&A*, 474, 653