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The ELODIE survey for northern extra-solar planets[⋆,⋆⋆,⋆⋆⋆]

I. Six new extra-solar planet candidates

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Abstract. Precise radial-velocity observations at Haute-Provence Observatory (OHP, France) with the ELODIE echelle spectrograph have been undertaken since 1994. In addition to several discoveries described elsewhere, including and following that of 51 Peg b, they reveal new sub-stellar companions with essentially moderate to long periods. We report here about such companions orbiting five solar-type stars (HD 8574, HD 23596, HD 33636, HD 50554, HD 106252) and one sub-giant star (HD 190228). The companion of HD 8574 has an intermediate period of 227.55 days and a semi-major axis of 0.77 AU. All other companions have long periods, exceeding 3 years, and consequently their semi-major axes are around or above 2 AU. The detected companions have minimum masses $m_2 \sin i$ ranging from slightly more than 2 $M_{\rm Jup}$ to 10.6 $M_{\rm Jup}$. These additional objects reinforce the conclusion that most planetary companions have masses lower than 5 $M_{\rm Jup}$ but with a tail of the mass distribution going up above 15 $M_{\rm Jup}$. The orbits are all eccentric and 4 out of 6 have an eccentricity of the order of 0.5. Four stars exhibit solar metallicity, one is metal-rich and one metal-poor. With 6 new extra-solar planet candidates discovered, increasing their total known to-date number to 115, the *ELODIE Planet Search Survey* yield is currently 18. We emphasize that 3 out of the 6 companions could in principle be resolved by diffraction-limited imaging on 8 m-class telescopes depending on the achievable contrast, and therefore be primary targets for first attempts of extra-solar planet direct imaging.

Key words. techniques: radial velocities – stars: binaries: spectroscopic – stars: low mass, brown dwarfs – planetary systems

1. Introduction

The *ELODIE Planet Search Survey*, an extensive radial-velocity northern survey of dwarf stars, has been underway for several years at the Haute-Provence Observatory (OHP, CNRS, France) using the ELODIE high-precision fiber-fed echelle spectrograph (Baranne et al. 1996) mounted on the Cassegrain focus of the 1.93-m telescope. This survey was initiated in 1994 by M. Mayor and D. Queloz in order to detect very low-mass stellar companions and allowed them to discover the first extra-solar planet (51 Peg b) orbiting a solar-type star (Mayor & Queloz 1995). This discovery was followed by a number of subsequent detections of extra-solar planets with ELODIE. Some of these results have previously been published.

This survey is part of a large effort aiming at an extra-solar planet search through radial-velocity measurements since several other planet surveys with a sensitivity $K_1 > 10\,{\rm m\,s^{-1}}$ are underway elsewhere. A list of the most productive ones includes the *Geneva Southern Planet Search Programme*, carried out with the CORALIE spectrograph mounted on the 1.2-m Euler swiss telescope (Queloz et al. 2000b; Udry et al. 2000a) at ESO–La Silla observatory, the *California & Carnegie Planet Search* with the HAMILTON spectrograph at the Lick Observatory (Marcy & Butler 1992) and the HIRES spectrograph mounted on the 10-m Keck-1 telescope (Vogt et al. 1994) at the W. M. Keck Observatory, the *G-Dwarf Planet Search* also performed with the HIRES spectrograph at Keck Observatory (Latham 2000), the *Anglo-Australian Planet Search* with the UCLES echelle spectrograph mounted on the 3.92-m Anglo-Australian Telescope (Tinney et al. 2001), the *AFOE Planet Search* (Korzennik et al. 1998) using the AFOE

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⋆ Based on observations made at the Haute-Provence Observatory (operated by French CNRS), the 1.2-m Euler swiss telescope at ESO–La Silla Observatory (Chile) and the 1.52-m ESO telescope also at La Silla Observatory.

⋆⋆ The ELODIE measurements discussed in this paper 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/410/1039`

⋆⋆⋆ Appendix A is only available in electronic form at
`http://www.edpsciences.org`

spectrograph mounted on the 1.5-m telescope at the Whipple Observatory and the *McDonald Planetary Search* (Cochran & Hatzes 1994) using the McDonald Observatory 2.7-m telescope coude spectrograph.

115 planet candidates, including 11 planetary systems, with minimum masses lower than 18 M_{Jup} and down to sub-Saturnian planets (Marcy et al. 2000; Pepe et al. 2002), have been detected so far, with periods from slightly less than 3 days to about 15 years. This should permit us to obtain more robust conclusions about the mass function estimation, and notably its fast rise towards lower masses, the relative metal content of the parent stars and constraints on the so-called *brown dwarf desert* at separations of a few AU (Halbwachs et al. 2000) and on the emerging *period desert* between 10 and 70 days (Udry et al. 2002), crucial ingredients to the understanding of planet formation mechanisms.

This paper is the first of a series devoted to the discovery of extra-solar planet candidates in the framework of the *ELODIE Planet Search Survey*. It reports on the detection of six new candidates, with minimum planetary masses ($m_2 \sin i$) in the range 2 to 11 Jovian masses. Five of these are orbiting F8 or G0 dwarf stars and one is found around a G5IV star. They are all but one long-period objects on little to moderately elongated orbits: three periods are found to be greater than 1500 days, the shortest one is 227.55 days and the orbital eccentricities are of the order of 0.5 for four objects and close to 0.3 for the two other ones. These discoveries, together with 3 others announced during the *Scientific Frontiers in Research on extra-solar Planets* conference in Washington (June 2002), bring the number of planets discovered with ELODIE up to 18.

The next section describes the sample of the *ELODIE Planet Search Survey* and summarizes the planet candidates it has allowed to detect up to now.

The basic properties of the stars harboring the six new companions are given in Sect. 3. Section 4 presents the radial-velocity data and the orbital solutions for the companions. The case of HD 13507, suspected for some time to harbor a planet but that actually has a low mass star companion, is exposed in Appendix A.

2. The ELODIE Planet Search Survey

The original sample of Mayor & Queloz (1995) contained 142 stars, out of which 51 Peg. The main selection criterion of these G and K dwarfs was their radial-velocity non-variability according to the anterior CORAVEL survey (Duquennoy et al. 1991; Duquennoy & Mayor 1991). The sample was largely modified in 1996 and later, so that the to-date survey sample size amounts up to 372 stars. Among the present sample, only 71 stars remain from the original list (active and/or too faint stars of this list were excluded) and 259 additional stars were included with the following criteria: $m_V \leq 7.65$, $\delta > 0\,^\circ$, $v \sin i$ (from CORAVEL) < 4 km s^{-1}, CORAVEL non-variability, spectral type from F8 to M0. Both lists are now forming the main programme with 330 objects.

In addition to these main programme stars, for follow-up or phase-coverage reasons based on the large access one can have to a 2 m-class telescope observing time, the sample was more recently complemented with 42 stars common with other programmes, among which 32 stars, with *V* magnitudes up to 9, were identified as variable by the Keck *G–Dwarf Planet Search* (Latham 2000). One star, HD 209458, was in our main programme and now also belongs to the collaborative effort with the *G–Dwarf Planet Search*.

The *Geneva Southern Planet Search programme* and the *ELODIE Planet Search Survey* have distinct stars samples, based on the declination, although the former may occasionally support the monitoring of a usually faint, low declination ELODIE programme star.

The planetary companion detection is based on the stellar radial-velocity reflex motion produced by gravitational interaction between companion and star. The ELODIE spectrograph, operating between 3850 and 6800 Å, has a spectral resolution of about 42 000. The planet survey makes use of its dual-fiber mode where a star and a reference thorium-argon calibration lamp are simultaneously observed to monitor and correct the instrumental drift and to achieve the required high precision. The signal-to-noise ratio per pixel for $m_V = 7.65$ stars is about 100 for a 15-min observation under good atmospheric conditions at OHP. In order to achieve the most homogeneous observations, some exposures are duplicated in order to reach the target signal-to-noise. None, except for some special cases, are longer than 15 min in order that no differential instrumental drift between the two beams dominate the resultant accuracy. The total exposure time per source is dictated by the goal that the photon-noise be lower than the instrumental limit. The radial-velocity measurement is produced on-line by the ELODIE automatic reduction software which cross-correlates the observed stellar spectrum with a binary mask template (Baranne et al. 1996). Some improvements have been implemented in 2001 in those regions of the mask particularly rich in telluric absorption features (see for details Pepe et al. 2002) leading to a current instrument-limited precision better than 6 m s^{-1}.

The improved precision is demonstrated by the distribution of the weighted radial-velocity rms measured for 111 constant stars in our sample (Fig. 3). We corrected the measured dispersions for the contribution of the photon noise. The instrumental error can be well estimated by the rms values of the low-dispersion tail of the histogram. The median of this distribution is 7.8 m s^{-1} and we find that 20% of these constant stars exhibit a velocity dispersion lower than 6 m s^{-1}. We also show in Fig. 4 our data for 4 constant stars with dispersions lower than 6.5 m s^{-1} (photon noise included). Finally, the residuals to the orbital solution obtained with ELODIE for 70 Vir (Naef et al. 2003a) are 6.1 m s^{-1} (photon noise included). The photon noise error of the 70 Vir measurements is $\epsilon_{phot} = 2.8$ m s^{-1}. The instrumental error inferred from this long series of values is: $\epsilon_{instr} = (6.1^2 - 2.8^2)^{1/2} = 5.4$ m s^{-1}.

More recent improvements in the telluric absorption features treatment have allowed us to reduce systematic yearly velocity effects that were still visible for some stars in our sample. This is for example the case for HD 33636 where the residuals to the fitted orbit could be reduced by a factor of almost two.

A total of more than 9000 measurements, spread over observing periods that are programmed about once every month,

Table 1. The 18 planet candidates with $m_2 \sin i < 11\ M_{\rm Jup}$ detected with ELODIE at Haute-Provence Observatory.

Candidate	References
51 Peg b	Mayor & Queloz (1995)
14 Her b	Udry et al. (2000b), Naef et al. (2003a)
Gl 876 b$^{\bullet}$	Delfosse et al. (1998)
HD 209458 b$^{\diamond}$	Mazeh et al. (2000)
HD 190228 b*	Sivan et al. (2000) and this paper
HD 8574 b*	this paper
HD 50554 b*†	this paper
HD 74156 b*	Naef et al. (2003a)
HD 74156 c*	Naef et al. (2003a)
HD 80606 b$^{\star\circ}$	Naef et al. (2001a)
HD 106252 b*†	this paper
HD 178911 Bb$^{\circ\star}$	Zucker et al. (2002)
HD 20367 b*	Udry et al. (2002)
HD 23596 b*	this paper
HD 33636 b*‡	this paper
HD 37124 c$^{*\natural}$	Udry et al. (2002)
HD 150706 b*	Udry et al. (2002)
GJ 777 Ab$^{*\flat}$	Udry et al. (2002), Naef et al. (2003b)

$^{\bullet}$ See also Marcy et al. (1998).
$^{\diamond}$ See also Charbonneau et al. (2000), Henry et al. (2000).
* Announced in ESO Press Release nb 07/01 (April 4, 2001).
† Confirmed by Fischer et al. (2002).
$^{\circ}$ Variability detected by the Keck *G–Dwarf Planet Search*.
‡ Independently announced by Vogt et al. (2002).
* Announced during the Scientific Frontiers in Research on extra-solar Planets conference, Washington, June 2002.
$^{\natural}$ See also Butler et al. (2003).
$^{\flat}$ HD 190360 b.

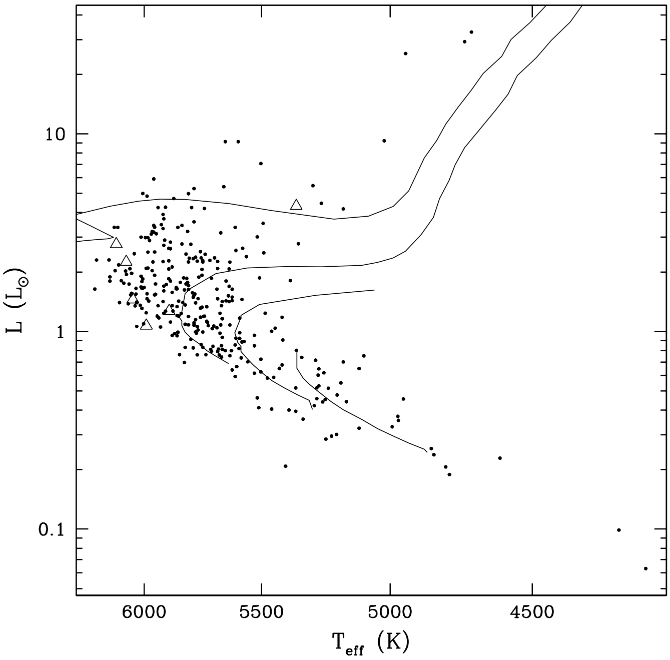

Fig. 1. The Hertzsprung-Russel diagram for the ELODIE main programme sample stars. The six stars with new planet candidates are shown as open triangles. The four curves are the solar metallicity evolutionary tracks for 0.8, 0.9, 1.0 and 1.25 $M_{\odot}$ from Geneva models (Schaller et al. 1992).

have been performed since the beginning of the programme at OHP. All stars but a few ones have been observed more than 10 times and in average almost 20 times but those presenting indications of variations may have been observed more than 50 times.

Table 1 lists all the planet candidates discovered so far with ELODIE having $m_2 \sin i \leq 11\ M_{\rm Jup}$ including the six presented in this paper and four others also recently announced. More massive companions, with minimum masses in the range 20–75 $M_{\rm Jup}$, among which HD 127506, HD 174457 and HD 185414, have been discovered with ELODIE (Naef et al. 2000b; Naef et al. in prep.). A peculiar case, HD 166435, has also emerged from the *ELODIE Planet Search Survey* observations. This star presents a chromospheric activity stable enough to mimic a short period Keplerian signature. Therefore, any radial-velocity variation potentially due to a short period companion is now first checked against such activity using line bisector variations, that have been shown to be a robust diagnostic by Queloz et al. (2001).

The list in Table 1 includes HD 209458 b (Mazeh et al. 2000), the only extra-solar planet for which transits were observed. Photometric transits were obtained (Charbonneau et al. 2000) with timing predictions computed from ELODIE monitoring and communicated to D. Charbonneau and collaborators. The first spectro-photometric transit was observed with ELODIE (Queloz et al. 2000a). The photometric and spectroscopic transits yielded notably the planet radius, the rotation direction with regard to that of its primary and the mean density ($0.3\ {\rm g\,cm^{-3}}$), essential to assess the gaseous nature of the planets. Two planet candidates in Table 1 were found around stars not belonging to the ELODIE main programme: HD 178911 Bb, a planetary companion in a stellar triple system (Zucker et al. 2002), and HD 80606 b, the extra-solar planet having the highest orbital eccentricity known so far (Naef et al. 2001a). They are both belonging to the *G-Dwarf Planet Search* programme carried out at the Keck telescope. Also, Gl 876 b, which is presently in the closest extra-solar planetary system known, was discovered as a by-product of an M-dwarf multiplicity statistical study carried out with the OHP-ELODIE and ESO-FEROS spectrographs and with the Canada-France-Hawaii Telescope (CFHT) PUE'O adaptive optics imaging system by a Grenoble-Geneva team (Delfosse et al. 1998), and independently by Marcy et al. (1998). Later, the presence of two planets on resonant orbits with periods in the ratio 2:1 that were masqueraded by a unique, more eccentric one, was recognized by Marcy et al. (2001).

Figure 1 shows the Hertzsprung-Russell diagram of the 317 stars in the *ELODIE Planet Search Survey* main programme sample for which an HIPPARCOS entry exists. The six stars harboring planet candidates discovered with ELODIE, presented in this paper, are shown with distinctive symbols. $T_{\rm eff}$ is derived from the HIPPARCOS $B - V$ by using the calibration of

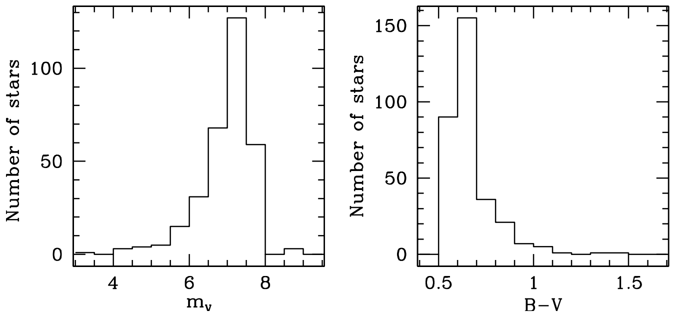

Fig. 2. The histograms of m_V and $B - V$ for the ELODIE main programme sample stars.

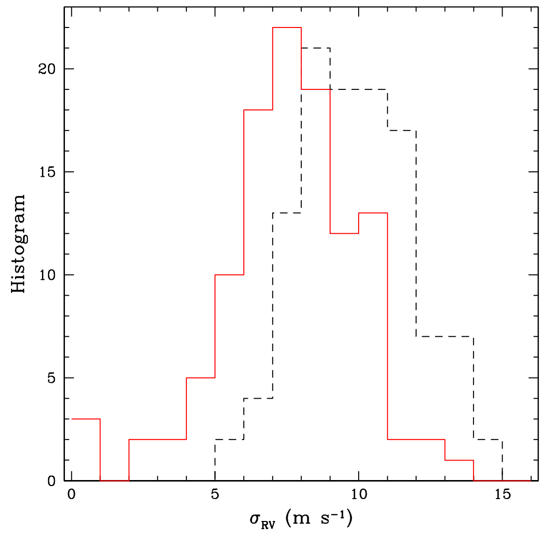

Fig. 3. Histogram of ELODIE radial-velocity weighted rms for constant stars. The 1723 measurements of 111 stars having $P(\chi^2) \geq 0.05$ and $N_{\rm meas} \geq 5$ have been used for the plot. These selection criteria are sufficient for eliminating highly active stars but lower activity objects can still be present in the sample. The solid curve represents the distribution of the weighted rms corrected (quadratically) for the photon noise. The main error sources still present in these corrected dispersions are the instrumental error and the stellar jitter. The median of this distribution is 7.8 m s^{-1} and 20% of the stars in this sample have weighted rms lower than 6 m s^{-1}. This latter value is a good estimate of the ELODIE instrumental error. We show for comparison the distribution obtained without correcting for the photon noise (dashed line).

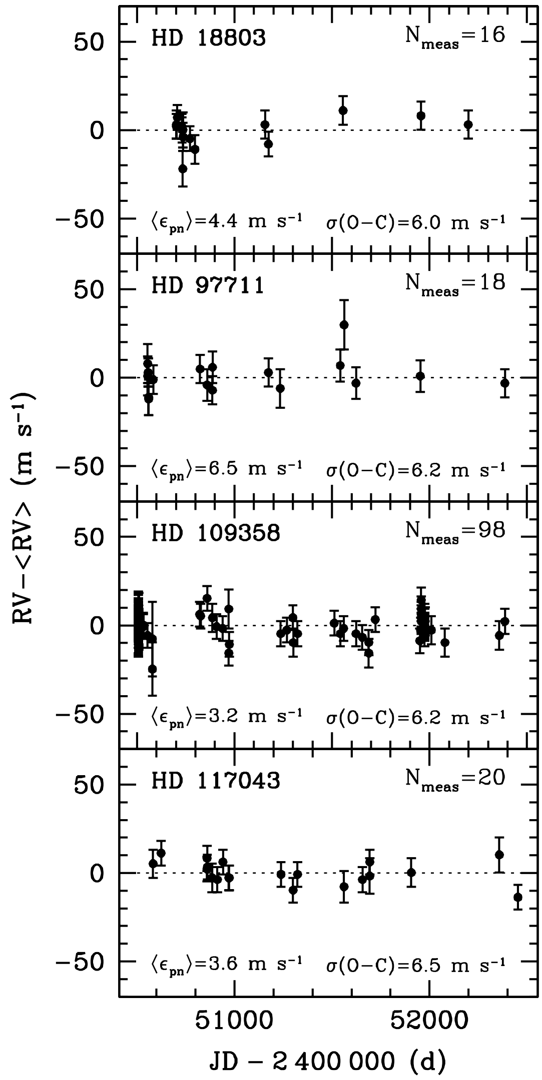

Fig. 4. Radial-velocity measurements in km s^{-1} versus time for four standard stars of the ELODIE programme sample: HD 18803, HD 97711, HD 109358 and HD 117043. The mean photon noise $\langle\epsilon_{\rm pn}\rangle$ is indicated at the lower left of each frame and the measurements photon noise-weighted rms error at the lower right. The time span of these measurements is similar to that for the six stars with planet candidates.

Flower (1996)[1], except for the six planet-candidate hosts for which the effective temperatures listed in Table 2 have been used, and L from HIPPARCOS apparent magnitude and parallax and the bolometric correction given by Flower's calibration.

In Fig. 2, the histograms of m_V and $B - V$ for the same stars as in Fig. 1, show a clear cut-off in magnitude dictated by the ELODIE performances and a range in spectral type with a pronounced bias toward G0–G5 dwarfs and a strict cut-off at the F8 spectral type.

[1] Note that the coefficients of the calibration printed in Flower (1996) are incorrect; we rather used the coefficients directly obtained from the author.

3. Stellar properties

The six stars found to harbour planetary companions are HD 8574, HD 23596, HD 33636, HD 50554, HD 106252 and HD 190228. Their basic characteristics are summarized in Table 2.

Spectral types, apparent magnitudes, color indexes, parallaxes and proper motions were all taken from the HIPPARCOS catalogue (ESA 1997). The bolometric corrections of all stars were derived from $B - V$ by using the calibration of Flower (1996).

The atmospheric parameters $T_{\rm eff}$, $\log g$, $\xi_{\rm t}$ and [Fe/H] and the stellar masses M_* are from Santos et al. (2003). The projected stellar rotational velocities, $v \sin i$, were obtained using the mean ELODIE cross-correlation functions (CCF) dip width (Baranne et al. 1996), except for HD 106252, and the calibration by Queloz et al. (1998). For HD 106252, $v \sin i$ has been

Table 2. Observed and inferred stellar parameters for the six stars.

		HD 8574	HD 23596	HD 33636
HIP		6643	17 747	24 205
Sp. type		F8	F8	G0
m_V		7.12	7.25	7.00
$B-V$		0.577 ± 0.011	0.634 ± 0.009	0.588 ± 0.016
π	(mas)	22.65 ± 0.82	19.24 ± 0.85	34.85 ± 1.33
Distance	(pc)	44.2 ± $^{1.7}_{1.5}$	52.0 ± $^{2.4}_{2.2}$	28.7 ± 1.1
$\mu_\alpha \cos(\delta)$	(mas yr^{-1})	252.59 ± 0.76	53.56 ± 0.68	180.83 ± 1.07
μ_δ	(mas yr^{-1})	−158.59 ± 0.55	21.06 ± 0.55	−137.32 ± 0.64
M_V		3.89	3.67	4.71
B.C.		−0.034	−0.029	−0.046
L	($L_\odot$)	2.25	2.76	1.07
$T_{\rm eff}$	(K)	6080 ± 50	6125 ± 50	5990 ± 50
$\log g$	(cgs)	4.41 ± 0.15	4.29 ± 0.15	4.68 ± 0.15
$\xi_{\rm t}$	(km s^{-1})	1.25 ± 0.10	1.32 ± 0.10	1.22 ± 0.10
[Fe/H]		0.05 ± 0.07	0.32 ± 0.05	−0.05 ± 0.07
$W_{\lambda,\rm Li}$	(mÅ)	52.1	76.7	49.5
$\log n$(Li)		2.56 ± 0.09	2.81 ± $^{0.11}_{0.07}$	2.46 ± $^{0.09}_{0.10}$
$v \sin i$	(km s^{-1})	4.04 ± 0.61	3.59 ± 0.59	2.79 ± 0.65
M_*	($M_\odot$)	1.17	1.30	1.12
		HD 50554	**HD 106252**	**HD 190228**
HIP		33 212	59 610	98 714
Sp. type		F8	G0	G5IV
m_V		6.84	7.41	7.30
$B-V$		0.582 ± 0.008	0.635 ± 0.007	0.793 ± 0.006
π	(mas)	32.23 ± 1.01	26.71 ± 0.91	16.10 ± 0.81
Distance	(pc)	31.0 ± $^{1.0}_{0.9}$	37.4 ± $^{1.3}_{1.2}$	62.1 ± $^{3.3}_{3.0}$
$\mu_\alpha \cos(\delta)$	(mas yr^{-1})	−37.29 ± 0.93	23.77 ± 0.91	104.91 ± 0.37
μ_δ	(mas yr^{-1})	−96.36 ± 0.50	−279.41 ± 0.53	−69.85 ± 0.57
M_V		4.38	4.54	3.33
B.C.		−0.038	−0.061	−0.176
L	($L_\odot$)	1.45	1.27	4.31
$T_{\rm eff}$	(K)	6050 ± 50	5890 ± 50	5360 ± 40
$\log g$	(cgs)	4.59 ± 0.15	4.40 ± 0.15	4.02 ± 0.10
$\xi_{\rm t}$	(km s^{-1})	1.19 ± 0.10	1.06 ± 0.1	1.12 ± 0.08
[Fe/H]		0.02 ± 0.06	−0.01 ± 0.07	−0.24 ± 0.06
$W_{\lambda,\rm Li}$	(mÅ)	46.6	9.7	8.8
$\log n$(Li)		2.48 ± 0.10	1.62 ± $^{0.23}_{0.37}$	1.05 ± $^{0.25}_{0.42}$
$v \sin i$	(km s^{-1})	3.32 ± 0.59	1.74 ± 0.25	<1
M_*	($M_\odot$)	1.11	1.02	0.83

derived from CCFs obtained with CORALIE and the calibration in Santos et al. (2002).

Table 2 also gives for each star the equivalent width $W_{\lambda,\rm Li}$ of the λ6707.8 Å Li I line, as measured on the co-addition of all the available ELODIE spectra, corrected for the spectrograph straight light. It can be seen that all stars exhibit a lithium absorption feature which is rather strong except for two of them, HD 106252 and HD 190228. Lithium abundances, scaled to $\log n(\rm H) = 12$, were derived following the method described in Naef et al. (2001b) by using the curves of growth published by Soderblom et al. (1993) and our tabulated $T_{\rm eff}$. The errors were estimated by assuming temperature and equivalent width variations of $\pm 1\sigma$. The maximum abundance values are obtained by using $T_{\rm eff} + 1\sigma$ and $W_{\lambda,\rm Li} + 1\sigma$ and the minimum values correspond to $T_{\rm eff} - 1\sigma$ and $W_{\lambda,\rm Li} - 1\sigma$. The resulting errors are not symmetrical because the error on $W_{\lambda,\rm Li}$ is supposed to be symmetrical and equal to ±5 mÅ.

The Ca II H absorption feature was extracted for the six stars as a chromospheric activity diagnostic. Figure 5 displays the spectra of the Ca II H line region obtained by the co-addition of all ELODIE spectra available for each star. None of the stars shows an appreciable emission. However, in this region, the ELODIE spectra do not usually have a high signal-to-noise ratio preventing us from the extraction of meaningful values of the $\log(R'_{HK})$ indicator. The apparent absence of emission does therefore not preclude a mild activity.

4. Orbital solutions

The achieved precision (photon noise + instrumental error) of the ELODIE radial-velocity measurements, although improved since the beginning of the *ELODIE Planet Search Survey* (see Sect. 2), is of the order of 10 m s^{-1} for these targets over the time span of the reported observations. The 254 individual

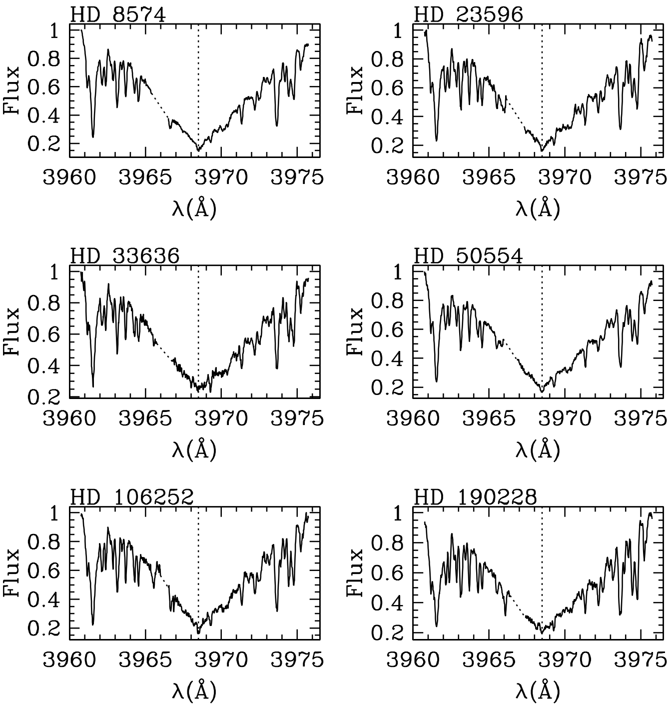

Fig. 5. The Ca II H line region for the six stars extracted from the co-addition of all spectra available for each star. The 3968.49 Å Ca II H line is indicated by a dotted line. None of the stars exhibits any clear trace of chromospheric emission feature in the line core (see text).

high-precision ELODIE radial velocities (+5 CORALIE measurements) obtained for the six planet-candidate host stars are available in electronic form at the CDS in Strasbourg. All these measurements are displayed in Figs. 6 and 7 which also show the orbital solutions, resulting from the best Keplerian fit and described below for each star.

We checked all solutions against false-alarms with Fourier transform analysis and found negligible (below the 1% level) false-alarm probabilities. We also checked their fit errors with Monte-Carlo simulations provided within the ORBIT programme described in Forveille et al. (1999). To this end, for each orbital solution, we ran 10 000 trials to derive Monte-Carlo estimates of the 1 and 3 σ confidence intervals. None of the solution displays a noticeable discrepancy with these simulations except in three cases for a few parameters, as mentioned in the text below.

4.1. HD 8574

We obtained a total of 41 ELODIE high-precision radial-velocity measurements for HD 8574 which was observed since Jan. 11, 1998 (JD = 2 450 825). We list in Table 3 the fitted orbital elements to these measurements together with the computed minimum mass $m_2 \sin i = 2.11\,M_{\rm Jup}$ of the planetary companion, assuming a primary star mass of $1.17\,M_{\odot}$. Our discovery of a companion of $m_2 \sin i = 1.95\,M_{\rm Jup}$ had been announced by the April 4th ESO Press Release[2]. The orbital solution presented here results from additional measurements obtained since then which further improved it. The errors listed in Table 3 are derived from Monte-Carlo simulations. They do not differ appreciably from the fit errors assessing the quality of this solution despite the rather high value of $\chi^2_{\rm red}$.

[2] www.eso.org/outreach/press-rel/pr-2001/pr-07-01.html

The companion of HD 8574 has the lowest period (227.55 d), well constrained (0.3%) and the best covered in terms of number of orbital cycles of the six planet candidates. Accordingly, it has also the smallest semi-major axis ($a = 0.77$ AU, i.e. 17 mas). The slightly abnormal residuals from the fitted orbit yield a moderate "jitter" of 8.2 m s^{-1}, although the primary has no known activity and does not exhibit any clear one from the Ca II H line core (Fig. 5).

4.2. HD 23596

We obtained a total of 39 ELODIE high-precision radial-velocity measurements for HD 23596 which was observed since Jan. 10, 1998 (JD = 2 450 824). Table 3 gives the obtained orbital elements together with the minimum mass of the companion ($m_2 \sin i = 8.10\,M_{\rm Jup}$ assuming $M_* = 1.30\,M_{\odot}$). The computed semi-major axis of the planetary orbit is $a = 2.88$ AU, i.e. 55 mas. This solution seems to be well constrained as judged from the absence of abnormal residuals and the agreement between fit errors and Monte-Carlo simulations.

The planet of HD 23596 has the largest semi-major axis of the six candidate planets if we put aside the peculiar case of HD 33636. With a period of 4.28 yr, the candidate around HD 23596 belongs to the category of long period planets which is naturally growing with the time span of the on-going surveys. It is also a massive planet. We emphasize the metal-rich nature of the parent star, a characteristics not shared by any of the six other stars.

4.3. HD 33636

The fitted orbital elements for HD 33636 to its 42 ELODIE radial-velocity measurements obtained since Feb. 18, 1998 (JD = 2 450 863), plus 5 recent CORALIE measurements, are presented in Table 3. The velocity offset between the two instruments is an additional free parameter. Its fitted value is $\Delta RV_{\rm E-C} = 0.038 \pm 0.004$ km s^{-1}. The variability of the HD 33636 radial velocities has been evident for several years since the first measurements were done while the planet was at its periastron. With a primary mass of $1.12\,M_{\odot}$ given by Santos et al. (2003), we compute a minimum mass of $m_2 \sin i = 10.58\,M_{\rm Jup}$ and a semi-major axis of $a = 4.08$ AU, i.e. 142 mas, for the planet. It must be emphasized that the period is certainly not yet covered (see Fig. 7), a fact corroborated by the change of the fitted period with the addition of the measurements of our last observing campaign. At this stage, most of the constraints come from the impact of the eccentricity on the radial velocity curve shape. Therefore the period of 7.74 yr is presently badly constrained but other parameters should be less affected. Interestingly, Monte-Carlo simulations show that

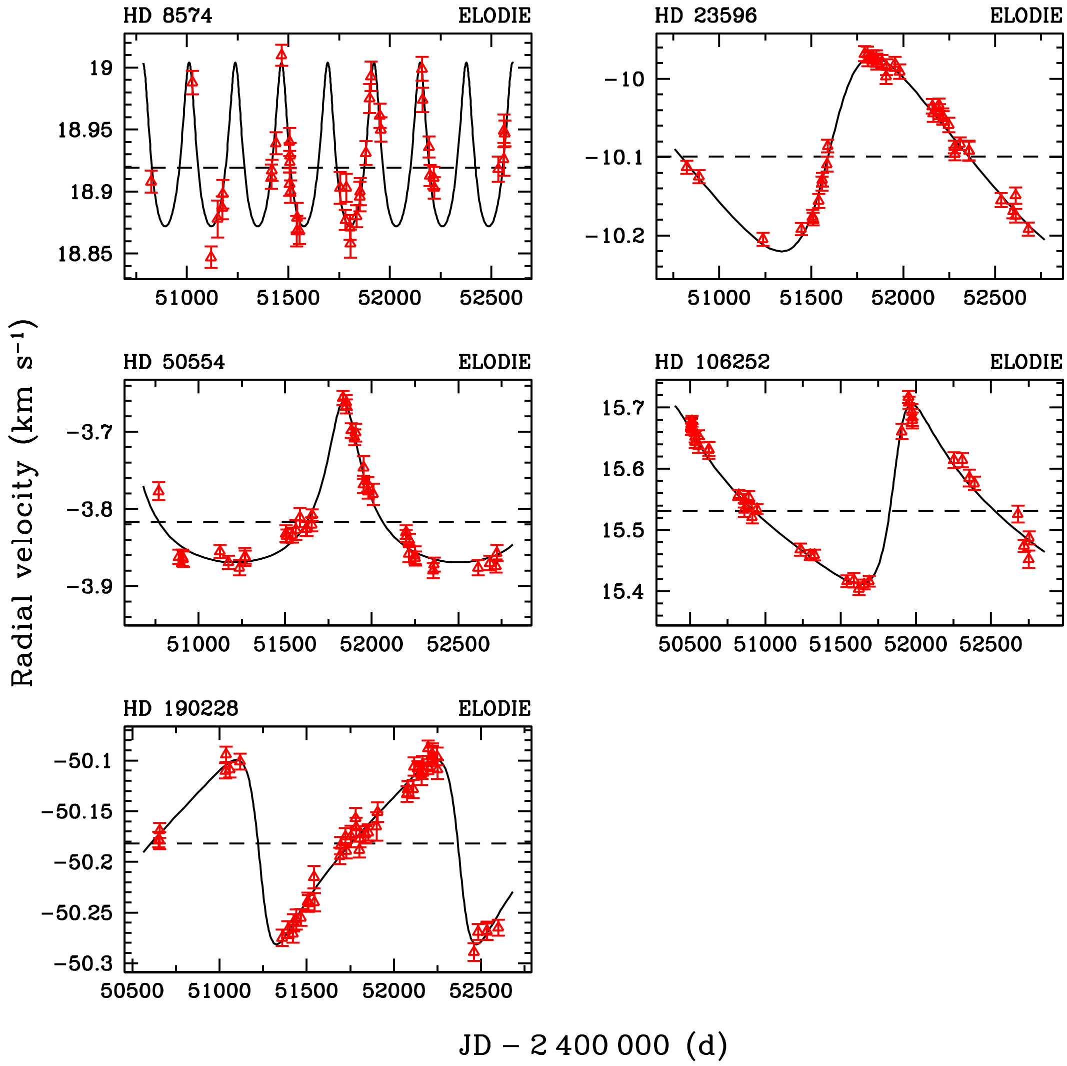

Fig. 6. ELODIE radial-velocity measurements in km s^{-1} versus time for all stars but HD 33636 shown in Fig. 7. Each measurement is plotted with an error bar equal to one estimated standard deviation. The orbital solution resulting from the best Keplerian fit, listed in Table 3 and discussed in the text, is superimposed.

the fit errors (listed in Table 3) are somewhat overestimated. We adopt the asymmetric Monte-Carlo errors for the period and keep the fit errors for the other parameters.

According to our preliminary orbital solution, HD 33636 b has the largest semi-major axis (4.08 AU) of the six planets. Despite its uncertainty, the period is long and therefore this new planet also belongs to the growing category of long period planets. It is also the most massive of our six candidates.

Vogt et al. (2002) have announced the independent detection of a companion of $m_2 \sin i = 7.7\, M_{\rm Jup}$. We have superimposed their orbital solution to ours in Fig. 7. The discrepancy between the two solutions is clearly due to their largely underestimated period. Our last campaign provides several measurements of good quality with which their orbital curve departs by 6 to 8 standard deviations of our most recent measurements. Moreover, the period in Vogt et al. (2002) is shorter than the time span of our measurements.

4.4. HD 50554

A total of 41 ELODIE precise radial-velocity measurements were obtained for HD 50554 since Nov. 16, 1997 (JD = 2 450 769). We list in Table 3 the fitted orbital elements together with the computed minimum mass $m_2 \sin i = 5.16\, M_{\rm Jup}$, assuming a primary star mass of 1.11 $M_\odot$. The confidence interval resulting from Monte-Carlo simulations is a bit larger than the fit error for the period. This is probably due to the peculiar weight of the first season measurement in the period estimation (see Fig. 6). We therefore took the confidence interval for the period instead of its fit error. The semi-major axis of 2.41 AU, i.e. 77 mas, is derived for this new planetary companion. The mean radial-velocity measurement error $\langle \epsilon_{\rm RV} \rangle$ and the weighted rms radial-velocity deviation σ(O – C) differ notably, yielding an appreciable "jitter" of 6.3 m s^{-1}.

Table 3. Fitted orbital elements to the radial-velocity measurements for the six stars, characteristics of their planet candidate companions and properties of the fit. When necessary, we replaced the fit error by the confidence interval value issued from Monte-Carlo simulations (see text). The $m_2 \sin i$ value is based on the M_* listed in Table 2. N_{meas} is the number of measurements that are effectively used in the orbital solution fit. $\langle \epsilon_{RV} \rangle$ is the mean measurement error and $\sigma(O-C)$ is the weighted rms of the residual. Comparison of the two values gives an indication of the amount of "jitter" which can also be appreciated from the χ^2_{red} value (the reduced χ^2 equal to χ^2/ν where ν is the number of degrees of freedom).

		HD 8574	HD 23596	HD 33636♮
P	(days)	227.55 ± 0.77	1565 ± 21	2828 $\pm^{1090}_{525}$
T	(JD)	2 451 467.5 ± 6.6	2 451 604 ± 15	2 451 211 ± 22
e		0.288 ± 0.053	0.292 ± 0.023	0.55 ± 0.10
γ	(km s^{-1})	18.919 ± 0.002	−10.099 ± 0.002	5.629 ± 0.035
w	(°)	3.6 ± 10.9	274.1 ± 3.9	340.2 ± 6.1
K_1	(m s^{-1})	66 ± 5	124 ± 3	168 ± 15
$a_1 \sin i$	(10^{-3} AU)	1.32	17.1	36.7
$f_1(m)$	(10^{-9} $M_\odot$)	5.97	274	822
$m_2 \sin i$	(M_{Jup})	2.11	8.10	10.58
a	(AU)	0.77	2.88	4.08
a_{min} †	(AU)	0.55	2.04	1.83
a_{max} ‡	(AU)	0.99	3.73	6.32
N_{meas}		41	39	47
$\langle \epsilon_{RV} \rangle$	(m s^{-1})	10.2	9.2	10.4
$\sigma(O-C)$	(m s^{-1})	13.1	9.2	9.0
χ^2_{red}		1.99	1.19	0.996
		HD 50554	HD 106252	HD 190228
P	(days)	1293 ± 37	1600 ± 18	1146 ± 16
T	(JD)	2 451 832.4 ± 15	2 451 871 ± 17	2 451 236 ± 25
e		0.501 ± 0.030	0.471 ± 0.028	0.499 $\pm^{0.047}_{0.024}$
γ	(km s^{-1})	−3.817 ± 0.002	15.531 ± 0.003	−50.182 ± 0.004
w	(°)	355.7 ± 4.4	292.2 ± 3.2	100.7 $\pm^{2.9}_{3.2}$
K_1	(m s^{-1})	104 ± 5	147 ± 4	91 ± 5
$a_1 \sin i$	(10^{-3} AU)	10.7	19.1	8.30
$f_1(m)$	(10^{-9} $M_\odot$)	96.9	362	58.1
$m_2 \sin i$	(M_{Jup})	5.16	7.56	3.58
a	(AU)	2.41	2.70	2.02
a_{min} †	(AU)	1.20	1.43	1.01
a_{max} ‡	(AU)	3.62	3.97	3.02
N_{meas}		41	40	51
$\langle \epsilon_{RV} \rangle$	(m s^{-1})	10.0	10.6	8.7
$\sigma(O-C)$	(m s^{-1})	11.8	10.5	8.0
χ^2_{red}		1.68	1.21	0.973

♮ 5 Coralie measurements are included in the solution for HD 33636 (see text).
† At periastron.
‡ At apoastron.

Our discovery of a companion of $m_2 \sin i = 4.9\,M_{Jup}$ had been announced by the ESO Press Release nb 07/01 (April 4, 2001). The orbital solution presented here results from additional measurements obtained since then which further improved it.

Fischer et al. (2002) have confirmed the detection of a companion with $m_2 \sin i = 3.7\,M_{Jup}$. Except for their K_1 and ω values that differ significantly from ours, the two orbital solutions are compatible. The better coverage of the radial-velocity maximum by our measurements probably explains the difference. The $m_2 \sin i$ discrepancy results from the rather large K_1 difference between the two solutions.

The Fischer et al. (2002) value of the chromospheric activity tracer $\log(R'_{HK})$ (−4.94), indicating a low activity for HD 50554, is not useful for explaining the observed "jitter", specially since the level of "jitter" is not well correlated to the $\log(R'_{HK})$ activity indicator for low-activity stars (Saar et al. 1998; Santos et al. 2000b).

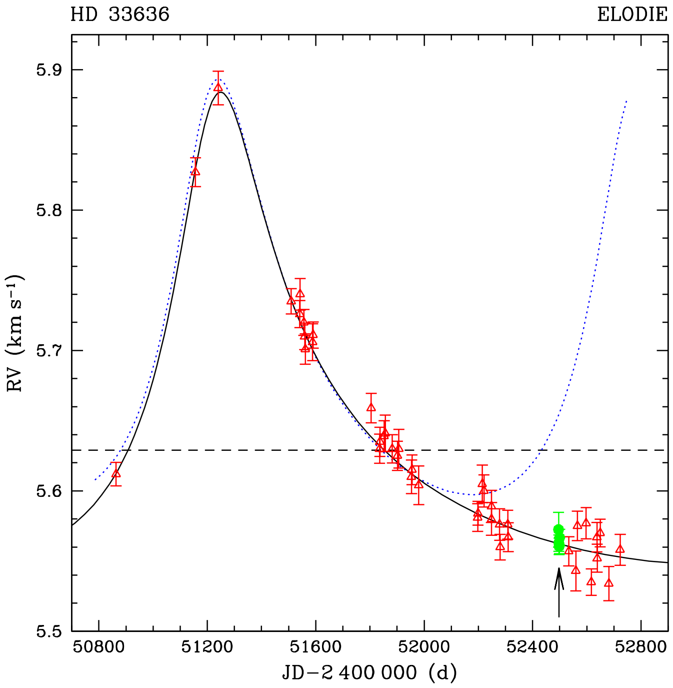

Fig. 7. ELODIE and CORALIE radial-velocity measurements in km s^{-1} versus time for HD 33636. The 5 CORALIE measurements are indicated by the arrow. Each measurement is plotted with an error bar equal to one estimated standard deviation. Since the computed period is not yet covered, the orbital solution is not displayed for the whole fitted period. The orbital solution resulting from the best Keplerian fit, listed in Table 3 and discussed in the text, is superimposed (solid line). The orbital solution published by Vogt et al. (2002) (dotted line) departs clearly from our solution at the epoch of the most recent measurements.

4.5. HD 106252

We gathered a total of 40 ELODIE high-precision radial-velocity measurements for HD 106252 which was observed since March 1, 1997 (JD = 2 450 509). In Table 3 are presented the fitted orbital elements to our measurements. With a primary mass of $M_* = 1.02\,M_\odot$, we compute a minimum mass of $m_2 \sin i = 7.56\ M_{\rm Jup}$ and a semi-major axis of 2.70 AU, i.e. 72 mas, for HD 106252 b. This solution is well constrained as confirmed by the absence of abnormal residuals. The Monte-Carlo confidence intervals are in good agreement with the fit errors.

The discovery of a companion with $m_2 \sin i = 6.8\,M_{\rm Jup}$ had also been announced by the ESO Press Release nb 07/01 (April 4, 2001). The orbital solution presented here results from additional measurements obtained since then which further improved it. With a period of 4.38 yr, this new planet also belongs to the growing category of long period planets. It is also a rather massive candidate.

Fischer et al. (2002) have confirmed the detection of a companion with $m_2 \sin i = 6.96\,M_{\rm Jup}$, a value in rather good agreement with ours. Their period is at more than 3σ from our value. This difference probably results in their poorer temporal coverage.

The Fischer et al. (2002) value of the chromospheric tracer $\log(R'_{HK})$ (−4.97), indicating a low activity for HD 106252, agrees with the absence of abnormal residuals.

4.6. HD 190228

We obtained a total of 51 ELODIE high-precision radial-velocity measurements for HD 190228 which was observed since Jul. 22, 1997 (JD = 2 450 652). We list in Table 3 the fitted orbital elements to these measurements together with the computed minimum mass $m_2 \sin i = 3.58\,M_{\rm Jup}$ assuming the primary star mass of $0.83\,M_\odot$ given by Santos et al. (2003). The semi-major axis $a = 2.02$ AU, i.e. 33 mas, is given as well. The confidence interval resulting from Monte-Carlo simulations is somewhat larger (indeed asymmetrically) than the fit error for the eccentricity and K_1. This could be caused by the bad coverage of the periastron (see Fig. 6). We therefore took the confidence interval for those two parameters instead of their fit error.

The discovery of a companion with $m_2 \sin i = 3.4\,M_{\rm Jup}$ had been announced in Sivan et al. (2000). The orbital solution presented here results from additional measurements obtained since then which slightly improved it.

Among the previous discoveries, more than a dozen planet candidates orbit sub-giant stars i.e. almost 20% of the total. Not yet statistically meaningful, this ratio however appears to be much larger than the proportion of sub-giant stars in the survey sample (19 stars among the *ELODIE Planet Search Survey* sample i.e. 5% of the total). The planet of HD 190228 is therefore not peculiar in this respect. On the contrary, HD 190228 is peculiar in terms of metallicity since it is the unique case in this paper sample with a metallicity value (−0.24 ± 0.06) quite below the solar abundance. It is also peculiar with respect to its spectral sub-type, since it is the coolest star of this sample.

5. Discussion

5.1. Existence of the companions

The orbital periods derived for the six planetary companions, spanning from 0.62 to 4.38 yr for five of them and even more for HD 33636 whose period is fairly imprecise, are much longer than the possible rotation periods of the primary stars, even though we have no individual estimation for most of them. This makes it very unlikely that any of the radial-velocity curves might be produced by activity spot phenomena as it has been observed for the short period variable HD 166435 (Queloz et al. 2001). Nevertheless we checked this for each star by computing the line bisectors of the observed CCFs and the linear correlation between the radial-velocity measurements and the bisector span. With maximum absolute values of the correlation coefficient below 0.23, we found no significant correlation, down to the 1σ level, for any of the six stars. The interpretation of the Doppler signature by the presence of a companion thus casts no doubt for the six planet candidates, even for the mildly active stars, a conclusion in agreement with that of Naef et al. (2000a) about long-period planet detectability around active stars.

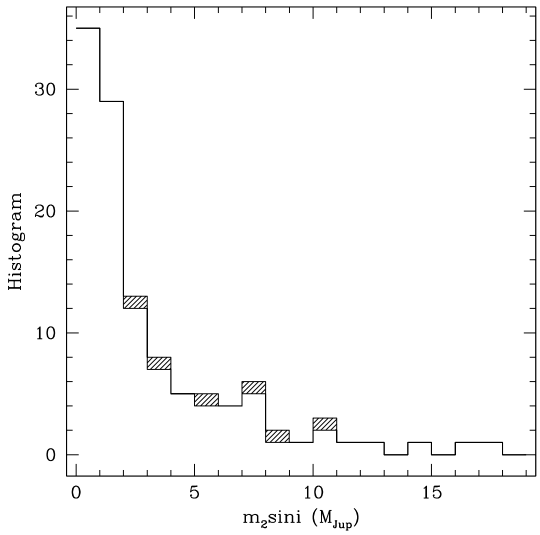

Fig. 8. $m_2 \sin i$ distribution for the 115 planet candidates discovered so far with $m_2 \sin i < 18\,M_{\rm Jup}$. The grey square areas point to the contribution of the additional six new candidates presented in this paper.

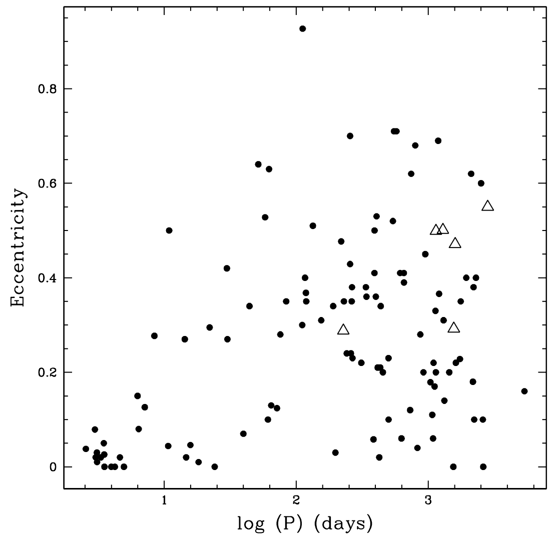

Fig. 9. The location of the 115 planet candidates discovered so far with $m_2 \sin i < 18\,M_{\rm Jup}$ in the diagram eccentricity versus period. The six new candidates are shown as open triangles.

5.2. $m_2 \sin i$ distribution and mass function

With six new planet candidates, we can usefully update the distribution of $m_2 \sin i$. Figure 8 displays the histogram of $m_2 \sin i$ of the 115 objects known so far, with $m_2 \sin i < 18\,M_{\rm Jup}$, including our six new candidates and about thirty other new candidates announced very recently. These additional objects, half of which below $m_2 \sin i = 2\,M_{\rm Jup}$ globally tend to smooth the cumulative frequency distribution and to fill some gaps present about $m_2 \sin i = 8\,M_{\rm Jup}$ (see Fig. 1 of Jorissen et al. 2001). Because the techniques used to estimate the deconvolved M_2 distribution (e.g. Jorissen et al. 2001) is sensitive to the sampling quality, one can infer that such an approach will be even more robust with the new, larger input frequency distribution. More specifically, the latter is likely to result in a smoother M_2 distribution, specially around and above $10\,M_{\rm Jup}$ that could make it less obvious that $10\,M_{\rm Jup}$ would be a quasi upper M_2 limit. Since this is only qualitative, it will be very interesting to know whether this study, applied to the new extra-solar planet sample, would rather lead to a vanishing distribution in the $15\,M_{\rm Jup}$ region.

5.3. Eccentricity versus period diagram

As seen above, the periods of all the companions are long, exceeding three years except for HD 8574. Their orbital eccentricities are close to 0.5 for four of the objects and about 0.3 for the two other ones. We have placed these six companions on a *e* vs. *P* diagram together with all the other known companions with $m_2 \sin i < 18\,M_{\rm Jup}$ (Fig. 9). Their location is dictated by the large values of the periods which is the natural effect of the bias towards long periods while the time span of the observing programmes increases. Apart from this, the diagram shows no particular trend for the six companions which are spread in a region of intermediate eccentricities, already well populated. The locations of our six new companions are in agreement with, and reinforce, the general behavior that tends to reproduce the spectroscopic binaries *e* vs. *P* distribution for long periods (Mayor et al. 2001; Mazeh & Zucker 2001), a rather paradoxical constraint on planet formation mechanisms.

5.4. Metallicity

It has been shown that the metallicity distribution of the planet-bearing stars is statistically 0.25 dex higher than for solar neighborhood stars (e.g. Santos et al. 2001). Since four of the six stars with new companions discussed here have solar metallicity, they will not help to statistically improve this conclusion. Moreover, while HD 23596 is over-metallic by 0.32 dex and therefore clearly falls in the upper part of the planet-bearing star distribution of Santos et al. (2001), HD 190228 is under-metallic by a similar amount (−0.24 dex). Both stars therefore almost compensates each other's effect on the distribution. The six stars will rather serve as additional material for further studies of metallicity distribution based on larger statistical samples.

5.5. Direct imaging feasibility

With separations at the orbital elongation larger than 50 mas, four out of the six new planet candidates could in principle be targets for diffraction-limited, i.e. adaptive optics, *K* band near infrared imaging on 8 m-class telescopes. The feasibility of such measurements is of course strongly dependent on the achievable contrast and therefore very questionable for long periods, cool Jupiter-like planets. Such imaging would anyway place useful constraints on the maximum mass and the orbital inclination of the companions. Altogether, the objective to image such companions clearly calls for very high contrast dedicated instruments (see e.g. Mouillet et al. 2001).

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Online Material

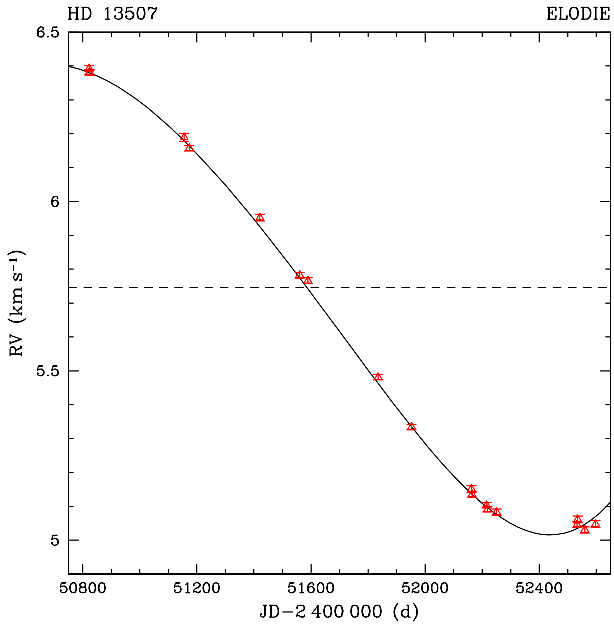

Fig. A.1. The ELODIE radial-velocity curve for HD 13507 versus time. The fit by the reflex motion due to the companion is superimposed to the measurements.

Appendix A: HD 13507

According to the HIPPARCOS catalogue, HD 13507 is a $m_V = 7.12$ G0 dwarf star with a parallax of 38.12 ± 0.89 mas but its absolute magnitude $M_V = 5.10$ $B - V$ (0.672 ± 0.007) rather suggest a G4 spectral type.

The atmospheric parameters and the mass of this star have been derived from a high signal-to-noise ELODIE spectrum by N.C. Santos (priv. comm.) in the way described in Santos et al. (2000a): $[\mathrm{Fe/H}] = 0.01 \pm 0.08$, $T_{\rm eff} = 5775 \pm 80$ K, $\log g = 4.71 \pm 0.17$ (cgs), $\xi_t = 1.33 \pm 0.11$ km s^{-1} and $M_* = 1.09\ M_\odot$.

A total of 19 ELODIE precise radial-velocity measurements were gathered for HD 13507 since Jan. 8, 1998 (HJD = 2 450 822). A preliminary but apparently good solution, based on a linear drift of 341 ± 8 m s^{-1} yr^{-1} and a Keplerian variation compatible with a planetary companion, that was announced as such, could be derived until mid 2002.

The later measurements obtained between july and december 2002 (see Fig. A.1) invalidated this interpretation and revealed instead a classical spectroscopic binary velocity curve, caused by a low mass star companion. This possibly explains the noticed discrepancy between the spectral type from HIPPARCOS and its photometry. The computed orbital parameters obtained from a still preliminary fit are: period $P \simeq 3000$ days, $e = 0.14$, $K_1 = 0.694$ m s^{-1}, minimum mass of the companion $m_2 \sin i = 52\ M_{\rm Jup}$, assuming a primary star mass of $1.09\ M_\odot$, and semi-major axis $a = 4.3$ AU, i.e. 164 mas. This solution is superimposed to the measurements, displayed in Fig. A.1.

We have searched for a companion to HD 13507 by adaptive optics imaging. An image was obtained in Bracketγ with PUE'O at the CFHT on August, 7th 2001 (HJD = 2 452 128.61) but no companion shows up at a 3σ level. A unique negative measurement leaves place to a possible alignment of the components but monitoring the binary with high dynamics imaging over a few years should resolve it and permit to derive the companion mass, a useful information for studies of sub-stellar objects statistics.