

The CORALIE survey for southern extra-solar planets

XII. Orbital solutions for 16 extra-solar planets discovered with CORALIE^{*,**}

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Abstract. This paper summarizes the information gathered for 16 still unpublished exoplanet candidates discovered with the CORALIE echelle spectrograph mounted on the Euler Swiss telescope at La Silla Observatory. Amongst these new candidates, 10 are typical extrasolar Jupiter-like planets on intermediate- or long-period ($100 < P \leq 1350$ d) and fairly eccentric ($0.2 \leq e \leq 0.5$) orbits (HD 19994, HD 65216, HD 92788, HD 111232, HD 114386, HD 142415, HD 147513, HD 196050, HD 216437, HD 216770). Two of these stars are in binary systems. The next 3 candidates are shorter-period planets (HD 6434, HD 121504) with lower eccentricities among which we find a hot Jupiter (HD 83443). More interesting cases are given by the multiple-planet systems HD 82943 and HD 169830. The former is a resonant $P_2/P_1 = 2/1$ system in which planet-planet interactions are influencing the system evolution. The latter is more hierarchically structured.

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

1. Introduction

For more than 5 years the CORALIE planet-search programme in the southern hemisphere (Udry et al. 2000a) has been ongoing at the 1.2-m Euler Swiss telescope – designed, built and operated by the Geneva Observatory – at La Silla Observatory (ESO/Chile). During these 5 years, CORALIE has allowed the detection (or has contributed to the detection) of 38 extra-solar planet candidates. This substantial contribution together with discoveries from various other programmes have provided a sample of more than 115 exoplanets that now permits us to point out interesting statistical constraints for the planet formation and evolution scenarios (see e.g. Mayor 2003; Udry et al. 2003d; Santos et al. 2003b, for reviews on different aspects of the orbital-element distributions or primary star properties).

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* Based on observations collected with the CORALIE echelle spectrograph on the 1.2-m Euler Swiss telescope at La Silla Observatory, ESO Chile.

** The precise radial velocities presented in this paper are 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/415/391>, except for the multi-planet systems that will appear in a future paper describing their dynamical evolutions, taking planet-planet interaction into account.

The majority of our CORALIE exoplanet candidates have been published in a series of dedicated papers¹, the latest among them reporting the detection of the shortest-period Hot Jupiter discovered by radial-velocity surveys around HD 73256 (Udry et al. 2003c) and the very interesting case of HD 10647 (Udry et al. 2003a), a star with a high IR excess indicative of the presence of a debris disk. The present paper of this series describes the CORALIE exoplanets that have not been published yet. This subsample includes candidates announced several months ago, rapidly after their detection to allow follow-up observations. It also includes some candidates with very long periods or that are members of multi-planet systems requiring a delay in their final analysis. Also, some of the new candidates correspond to very recent detections.

The paper is organized as follows. In the next section we summarize the primary star properties. The radial-velocity measurements and inferred orbital solutions will be presented in Sect. 3. In the last section we summarize the results and provide some concluding remarks.

¹ Another dedicated series has also been started for close binaries requiring a 2-dimensional correlation analysis for radial-velocity estimates. The method has already revealed a $2.5-M_{\text{Jup}}$ planet orbiting the primary (Zucker et al. 2003b) and a $19-M_{\text{Jup}}$ brown dwarf orbiting the secondary (Zucker et al. 2003a) of the HD 41004 close visual binary system.

Table 1. Observed and inferred stellar parameters for the stars hosting planets presented in this paper. Definitions and sources of the quoted values are given in the text. The age and rotational period estimates are based on calibrations of the R'_{HK} activity indicator (Donahue 1993; Noyes et al. 1984), whose reference source is also indicated: (S) for this paper following Santos et al. (2000), (H) for Henry et al. (1996) and (B) for Butler et al. (2002). The applied analyses and uncertainty estimates can be found in the quoted references.

HD	Sp	V	$B - V$	π [mas]	M_V	L [L_{\odot}]	T_{eff} [K]	$\log g$ [cgs]	[Fe/H]	M_{\star} [M_{\odot}]	$v \sin i$ [km s^{-1}]	$\log(R'_{\text{HK}})$	age [Gy]	P_{rot} [day]
6434	G3IV	7.72	0.613	24.80	4.69	1.12	5835	4.60	-0.52	0.79	2.3	-4.89 (H)	3.8	18.6
19994	F8V	5.07	0.575	44.69	3.32	3.81	6217	4.29	0.25	1.34	8.1	-4.77 (S)	2.4	12.2
65216	G5V	7.97	0.672	28.10	5.21	0.71	5666	4.53	-0.12	0.92	<1	-	-	-
82943	G0	6.54	0.623	36.42	4.35	1.50	6005	4.45	0.32	1.15	1.7	-4.82 (S)	2.9	18.0
83443	K0V	8.23	0.811	22.97	5.04	0.88	5454	4.33	0.35	0.90	1.4	-4.85 (B)	3.2	35.3
92788	G5	7.31	0.694	30.94	4.76	1.05	5821	4.45	0.32	1.10	1.8	-4.73 (S)	2.1	21.3
111232	G5V	7.59	0.701	34.63	5.29	0.69	5494	4.50	-0.36	0.78	1.2	-4.98 (H)	5.2	30.7
114386	K3V	8.73	0.982	35.66	6.49	0.29	4804	4.36	-0.08	0.68	1.0	-	-	-
121504	G2V	7.54	0.593	22.54	4.30	1.55	6075	4.64	0.16	1.18	2.6	-4.57 (S)	1.2	8.6
142415	G1V	7.33	0.621	28.93	4.64	1.14	6045	4.53	0.21	1.03	3.3	-4.55 (S)	1.1	9.6
147513	G3/5V	5.37	0.625	77.69	4.82	0.98	5883	4.51	0.06	1.11	1.5	-4.38 (S)	0.3	4.7
169830	F8V	5.90	0.517	27.53	3.10	4.59	6299	4.10	0.21	1.40	3.3	-4.82 (S)	2.8	8.3
196050	G3V	7.50	0.667	21.31	4.14	1.83	5918	4.34	0.22	1.10	3.1	-4.65 (S)	1.6	16.0
216437	G4IV/V	6.04	0.660	37.71	3.92	2.25	5887	4.30	0.25	1.06	2.5	-5.01 (H)	5.8	26.7
216770	K0V	8.11	0.821	26.39	5.22	0.79	-	-	0.23	0.90	1.4	-4.84 (H)	3.1	35.6

2. Parent star characteristics

The CORALIE planet-search targets have been selected from the Hipparcos catalogue (ESA 1997). Our planet-star subsample benefits thus from the photometric and astrometric information gathered by the satellite.

A high-resolution spectroscopic abundance study was performed for most of these stars by N.C. Santos in his study demonstrating the metallicity enrichment of stars with planets with regard to comparison “single” stars analysed in a homogeneous way (Santos et al. 2001, 2003b, and references therein). This study provides precise values of the effective temperatures, metallicities and gravity estimates, using a standard local thermodynamical equilibrium (LTE) analysis. These values have also been updated by using better recent oscillator strengths ($\log gf$) in the procedure (Santos et al. 2003a). From calibrations of the width and surface of the CORALIE cross-correlation functions (CCF; described in Santos et al. 2002), we also derive the stellar projected rotational velocity $v \sin i$ and [Fe/H] when not available from the spectral analysis. Like the majority of stars hosting planets, most of our candidates show a significant metal enrichment compared to the Sun, with the noticeable exception of HD 6434 (the second most deficient star hosting a planet known to date) and HD 111232.

From the colour index, the measured T_{eff} and the corresponding bolometric correction, we estimate the star luminosities² and we then interpolate the masses and ages in the grid of Geneva stellar evolutionary models with appropriate metal abundances (Schaller et al. 1992; Schaerer et al. 1993). For the brightest star in the sample we estimate, following Santos et al. (2000), an activity indicator from the reemission flux in the Ca II H absorption line. In some cases, this value is also available in the literature (mainly in Henry et al. 1996).

² When not available from the spectroscopic study, a photometric T_{eff} (following Flower 1996, not given in Table 1) is used to derive an indicative star luminosity.

Such an indicator is then used to derive calibrated estimates of the stellar rotational periods and ages (Noyes et al. 1984; Donahue 1993). Table 1 gathers the photometric, astrometric, spectroscopic information and inferred quantities available for our sample of stars hosting exoplanet candidates.

The activity indicator is, however, not always available in the literature or cannot be estimated from our spectra because of the star faintness (HD 65216, HD 114386). Calcium reemission can then be visually checked on the co-addition of the CORALIE best-S/N spectra. For our subsample, this is shown in Fig. 1 for the λ 3968.5 Å Ca II H absorption line region. A prominent reemission feature is clearly visible for HD 114386 and HD 147513, the latter presenting, moreover, a strong activity indicator. However, these stars are only slowly rotating and no large influence on the radial-velocity measurements is then expected (Santos et al. 2000; Saar et al. 1998). Hints of reemission are also observed for HD 65216, HD 83443, HD 142415, and HD 216770 but again $v \sin i$ is fairly low for these stars for which only a moderate jitter might be expected.

Some stars in this sample deserve a few more comments:

– *HD 6434 (HIP 5054)*: The star is classified as subgiant. Taking into account its low metallicity, the derived absolute magnitude, effective temperature and gravity estimates also support the slightly evolved status of the star.

– *HD 19994 (HIP 14954, HR 962, GJ 128A)*: The star is known to have a close physical M dwarf companion (GJ 128 B) a few arcseconds away (~ 100 AU; Hale 1994). Planets in binary systems are important for our understanding of planet formation because they seem to present different mass and orbital properties than planets orbiting single stars (Zucker & Mazeh 2002; Eggenberger et al. 2003; Udry et al. 2003d). The rotational velocity of HD 19994 is fairly large ($v \sin i = 8.1 \text{ km s}^{-1}$) thus, even if the star is not clearly active, some small radial-velocity jitter might be expected. Contamination from the

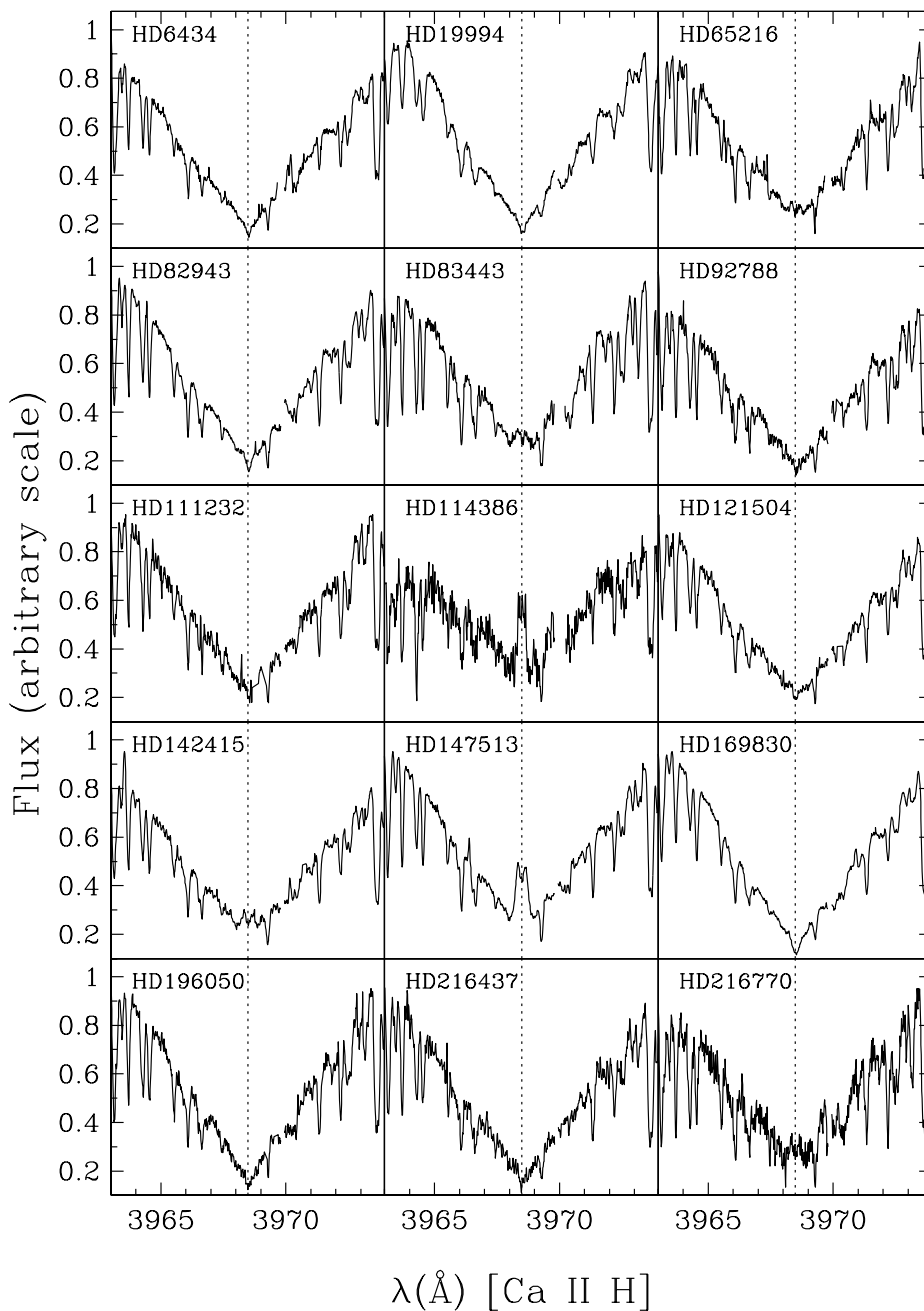


Fig. 1. λ 3968.5 Å Ca II H absorption line region of the summed CORALIE good spectra for our candidate stars. The dotted lines indicate the exact position of the absorption line centers. A clear reemission feature is visible for HD 114386 and HD 147513, whereas only hints of reemission are observed for HD 65216, HD 83443, HD 142415, and HD 216770. The spectra have been cleaned as much as possible from the pollution of the simultaneously recorded thorium-lamp reference spectra.

secondary could also be a concern although the 6.4 mag difference between the stars makes it very unlikely.

– *HD 82943 (HIP 47007)*: A fair amount of the easy-to-burn element ${}^6\text{Li}$ has been detected in the spectra of this star (Israeli et al. 2001, 2003) suggesting a planet engulfment in the late stages of the system formation, after the star has reached the Main Sequence. The not too deep convective zone of this G0 dwarf allows then for the survival of this element.

– *HD 111232 (HIP 62534)*: The high velocity ($V = 104.4 \text{ km s}^{-1}$) and low metallicity ($[\text{Fe}/\text{H}] = -0.36$)

of the star indicate that it probably belongs to the thick disk population. HD 111232 is a proposed binary in the Hipparcos catalogue (ESA 1997). It is one of the so-called *problem stars* for which an astrometric acceleration solution is provided (flagged “G” in the H59 field of the main catalogue). However, no companion with $\Delta V \leq 3.0$ was found close to the star (within $1.08''$) by speckle interferometry (Mason et al. 1998).

– *HD 121504 (HIP 68162)*: A visual companion (CPD –55:5793) is observed at a separation of $34.2''$ (Dommanget & Nys 1994). It is an A2 star of magnitude

$V = 9.17$ with different proper motions than HD 121504. The pair is thus not physical. No companion was found close to the star by speckle interferometry (Mason et al. 1998).

– *HD 142415 (HIP 78169)*: A Rosat-All-Sky-Survey X-ray source (1RXS J155740.7-601154) is observed close to the star, at $\sim 5''$. No bright companion was found close to the star by speckle interferometry measurements (Mason et al. 1998).

– *HD 147513 (HIP 80337, HR 6094, GJ 620.1A)*: The star was proposed to be a barium dwarf by Porto de Mello & da Silva (1997). A common proper motion white dwarf (WD; $V = 10$), at a projected distance of 5360 AU, could support the explanation of the origin of the barium feature by the process of mass transfer in a binary system, in which the secondary component accreted matter from the evolved primary, now the WD (see e.g. Jorissen et al. 1998, and references therein). To account for the observed large separation, Porto de Mello & da Silva (1997) invoke a possible ejection of the WD from an originally quadruple system also including HD 147513. In such a case, this would be the first known case of a planet orbiting a solar-type star in a binary system with the stellar companion in the last stage of its life. The influence on the planet evolution of the mass transfer between two stars is still poorly studied. The mentioned authors also include the star in the 0.3 Gyr old Ursa Major kinematical group. Although some doubts (but no rejection) were cast on the membership (King et al. 2003), it is worth noticing that the activity level, activity-derived age and metallicity (Table 1) correspond well to the Ursa Major group. Finally, no bright companion was found closer-in to the star by speckle interferometry measurements (Mason et al. 1998).

3. Radial-velocity data and orbital solutions

The radial-velocity measurements presented in this paper were obtained with the CORALIE echelle spectrograph mounted on the 1.2-m Euler Swiss telescope at La Silla Observatory (ESO, Chile). CORALIE is a similar but improved version of the ELODIE spectrograph at the Haute-Provence Observatory (CNRS, France). Details on the instrument design, reduction procedures as well as radial-velocity estimates based on simultaneous thorium-lamp measurements and cross-correlation technique can be found in Baranne et al. (1996).

The typical precision obtained with CORALIE is $\sim 3 \text{ m s}^{-1}$ for bright stars (Queloz et al. 2001b). However, due to the small size of the telescope, our sample stars (Udry et al. 2000a) are mainly photon-noise limited. For the derivation of the orbital solution an *instrumental* error of 3 m s^{-1} is quadratically added to photon noise. Then we only take into account the spectra with good signal-to-noise, typically corresponding to radial-velocity uncertainties below 10 to 15 m s^{-1} , depending on the star. Also, to improve the Doppler information extraction from the spectra, a new weighted cross-correlation scheme was developed (Pepe et al. 2002a). It is applied for the velocity estimates of most of the stars of this paper³.

³ The CORALIE numerical mask used in the cross correlation for the velocity estimate was built from a K0-dwarf spectrum. For much earlier spectral-type stars (typically $\leq G1$), the mismatch between the stellar spectrum and the template is enhanced by the weighted

3.1. The single-planet systems

To simplify the presentation of our results for the single-planet systems, the standard orbital parameters derived from the best fitted 1-Keplerian solution to the data are gathered in Table 2. Useful inferred planetary parameters and further information on the number of measurements used, their time coverage (*Span*) and the residuals (weighted rms) around the solutions ($\sigma(\text{O-C})$) are given as well. Finally, we also indicate the references for the detection announcements of these candidates⁴ (*Det.Ref.*). The corresponding phase-folded radial-velocity curves are displayed in Figs. 2 to 4 (top panel in each diagram). The residuals drawn as a function of the Julian date are displayed in the figures as well (bottom panels).

Simultaneous independent discoveries have been made for 3 of our candidates: by Fischer et al. (2001) for HD 92788 and by Jones et al. (2002) for HD 196050 and HD 216437. Their orbital solutions are very similar to ours (Table 2).

For most of the systems, the residuals measured around the derived solutions are compatible with the typical individual radial-velocity uncertainties. Some of them are, however, slightly larger ($\sim 10 \text{ m s}^{-1}$). In these cases, a slight level of activity can be invoked to explain the additional noise. HD 114386 is a good example with its clear activity level testified by the visible reemission in the Ca II H absorption line (Fig. 1). Another illustration is given by the similar early G dwarfs HD 121504 and HD 142415. They present light rotation and an activity level that can explain the somewhat large measured residuals. It is interesting to note here the similar values of $v \sin i$, $\log R'_{\text{HK}}$ and $\sigma(\text{O-C})$ for the two candidates.

In order to emphasize a relation between the residuals to the Keplerian solutions and stellar activity, we compared in a systematic way for all the candidates the obtained residuals with the shape of the spectral lines, estimated by the bisector inverse slope of our cross-correlation functions (BIS; Queloz et al. 2001a). Unfortunately, at this level of velocity variation ($\leq 10 \text{ m s}^{-1}$) and at the S/N of the CORALIE spectra, no definitive conclusion can be drawn. The same non-conclusive result was also obtained for HD 73256 which did not show any clear relation between the BIS parameter and the residuals around the 2.5-d solution, although the activity-induced radial-velocity jitter was undubitably emphasized by the simultaneous variations of the stellar photometric signal and the residuals (Udry et al. 2003a). We also searched in a systematic way, through

scheme and no improvement is obtained for the radial-velocity measurements. The usual cross correlation scheme is then used in such cases (Table 2).

⁴ At the IAU Symp. 202 in Manchester, we announced 6 CORALIE candidates (Mayor et al. 2000; Queloz et al. 2000; Udry et al. 2000b, 5 of them being described in this paper) and 1 further ELODIE candidate (Sivan et al. 2000). The proceedings of the IAU Symp. 202 have not yet appeared. Our 8 contributions to this conference describing the planet and brown-dwarf CORALIE and ELODIE new detections, the metallicity of stars hosting planets, the effect of stellar activity on radial-velocity measurements and a presentation of the new HARPS spectrograph (now running on the ESO 3.6-m at La Silla) are accessible from our *Exoplanets* web page: <http://obswww.unige.ch/Exoplanets/publications.html>

Table 2. CORALIE best Keplerian orbital solutions as well as inferred planetary parameters for the 1-planet systems. *Span* is the time interval in days between the first and last measurements. $\sigma(\text{O-C})$ is the weighted rms of the residuals around the derived solutions. *mask* is the template used in the cross-correlation scheme for the radial-velocity estimate (see Sect. 3). *Det.Ref.* is the reference to the planet detection announcement (conference or press release).

Parameter	HD 6434 b	HD 19994 b	HD 65216 b	HD 83443 b	HD 92788 b
	HIP 5054 b	HIP 14954 b	HIP 38558 b	HIP 47202 b	HIP 52409 b
<i>Det.Ref.</i>	Queloz et al. (2000)	Queloz et al. (2000)	Udry et al. (2003b)	Mayor et al. (2000)	Queloz et al. [†] (2000)
<i>P</i> [days]	21.998 ± 0.009	535.7 ± 3.1	613.1 ± 11.4	2.98565 ± 0.00003	325.0 ± 0.5
<i>T</i> [JD-2 400 000]	51 490.8 ± 0.6	50 944 ± 12	50 762 ± 25	51 497.5 ± 0.3	51 090.3 ± 3.5
<i>e</i>	0.17 ± 0.03	0.30 ± 0.04	0.41 ± 0.06	0.013 ± 0.013	0.35 ± 0.01
<i>V</i> [km s ⁻¹]	23.023 ± 0.001	19.335 ± 0.001	42.674 ± 0.002	29.027 ± 0.001	-4.467 ± 0.001
ω [deg]	156 ± 11	41 ± 8	198 ± 6	11 ± 11	279 ± 3
<i>K</i> [m s ⁻¹]	34.2 ± 1.1	36.2 ± 1.9	33.7 ± 1.1	58.1 ± 0.4	106.2 ± 1.8
<i>a</i> ₁ sin <i>i</i> [10 ⁻³ AU]	0.068	1.701	1.729	1.594	2.966
<i>f</i> (<i>m</i>) [10 ⁻⁹ M _⊙]	0.087	2.289	1.835	6.062	32.94
<i>m</i> ₂ sin <i>i</i> [M _{Jup}]	0.39	1.68	1.21	0.38	3.58
<i>a</i> [AU]	0.14	1.42	1.37	0.039	0.96
<i>N</i> _{meas}	130	48	70	257	55
<i>Span</i> [days]	1501	1519	1460	1455	1451
$\sigma(\text{O-C})$ [m s ⁻¹]	10.6	8.1	6.8	9.0	8.0
<i>mask</i>	weighted K0	K0	weighted K0	weighted K0	weighted K0
Parameter	HD 111232 b	HD 114386 b	HD 121504 b	HD 142415 b	HD 147513 b
	HIP 62534 b	HIP 64295 b	HIP 68162 b	HIP 78169 b	HIP 80337 b
<i>Det.Ref.</i>	Udry et al. (2003b)	Udry et al. (2002)	Queloz et al. (2000)	Udry et al. (2003b)	Udry et al. (2002)
<i>P</i> [days]	1143 ± 14	937.7 ± 15.6	63.33 ± 0.03	386.3 ± 1.6	528.4 ± 6.3
<i>T</i> [JD-2 400 000]	51 230 ± 20	50 454 ± 43	51 450 ± 2	51 519 ± 4	51 123 ± 20
<i>e</i>	0.20 ± 0.01	0.23 ± 0.03	0.03 ± 0.01	0.5 (fixed)	0.26 ± 0.05
<i>V</i> [km s ⁻¹]	104.4 ± 0.001	33.370 ± 0.001	19.617 ± 0.001	-11.811 ± 0.001	12.924 ± 0.001
ω [deg]	98 ± 6	273 ± 14	265 ± 12	255 ± 4	282 ± 9
<i>K</i> [m s ⁻¹]	159.3 ± 2.3	34.3 ± 1.6	55.8 ± 0.9	51.3 ± 2.3	29.3 ± 1.8
<i>a</i> ₁ sin <i>i</i> [10 ⁻³ AU]	16.39	2.875	0.325	1.579	1.377
<i>f</i> (<i>m</i>) [10 ⁻⁹ M _⊙]	450.0	3.604	1.140	3.517	1.248
<i>m</i> ₂ sin <i>i</i> [M _{Jup}]	6.80	1.24	1.22	1.62	1.21
<i>a</i> [AU]	1.97	1.65	0.33	1.05	1.32
<i>N</i> _{meas}	38	58	100	137	30
<i>Span</i> [days]	1181	1550	1496	1529	1690
$\sigma(\text{O-C})$ [m s ⁻¹]	7.5	10.2	11.6	10.6	5.7
<i>mask</i>	weighted K0	weighted K0	weighted K0	K0	weighted K0
Parameter	HD 196050 b	HD 216437 b	HD 216770 b		
	HIP 101806 b	HIP 113137 b	HIP 113238 b		
<i>Det.Ref.</i>	Udry et al. (2002) [‡]	Udry et al. (2002) [‡]	Udry et al. (2003b)		
<i>P</i> [days]	1321 ± 54	1256 ± 35	118.45 ± 0.55		
<i>T</i> [JD-2 400 000]	52 045 ± 66	50 693 ± 130	52 672 ± 3.5		
<i>e</i>	0.3 (fixed)	0.29 ± 0.12	0.37 ± 0.06		
<i>V</i> [km s ⁻¹]	61.342 ± 0.005	-2.278 ± 0.004	31.153 ± 0.002		
ω [deg]	147 ± 12	63 ± 22	281 ± 10		
<i>K</i> [m s ⁻¹]	55.0 ± 6.2	34.6 ± 5.7	30.9 ± 1.9		
<i>a</i> ₁ sin <i>i</i> [10 ⁻³ AU]	6.367	3.815	0.313		
<i>f</i> (<i>m</i>) [10 ⁻⁹ M _⊙]	19.74	4.694	0.291		
<i>m</i> ₂ sin <i>i</i> [M _{Jup}]	3.02	1.82	0.65		
<i>a</i> [AU]	2.43	2.32	0.46		
<i>N</i> _{meas}	31	21	16		
<i>Span</i> [days]	1364	1405	827		
$\sigma(\text{O-C})$ [m s ⁻¹]	7.2	7.2	7.8		
<i>mask</i>	weighted K0	weighted K0	weighted K0		

[†] Independently discovered by Fischer et al. (2001).

[‡] Independently discovered by Jones et al. (2002).

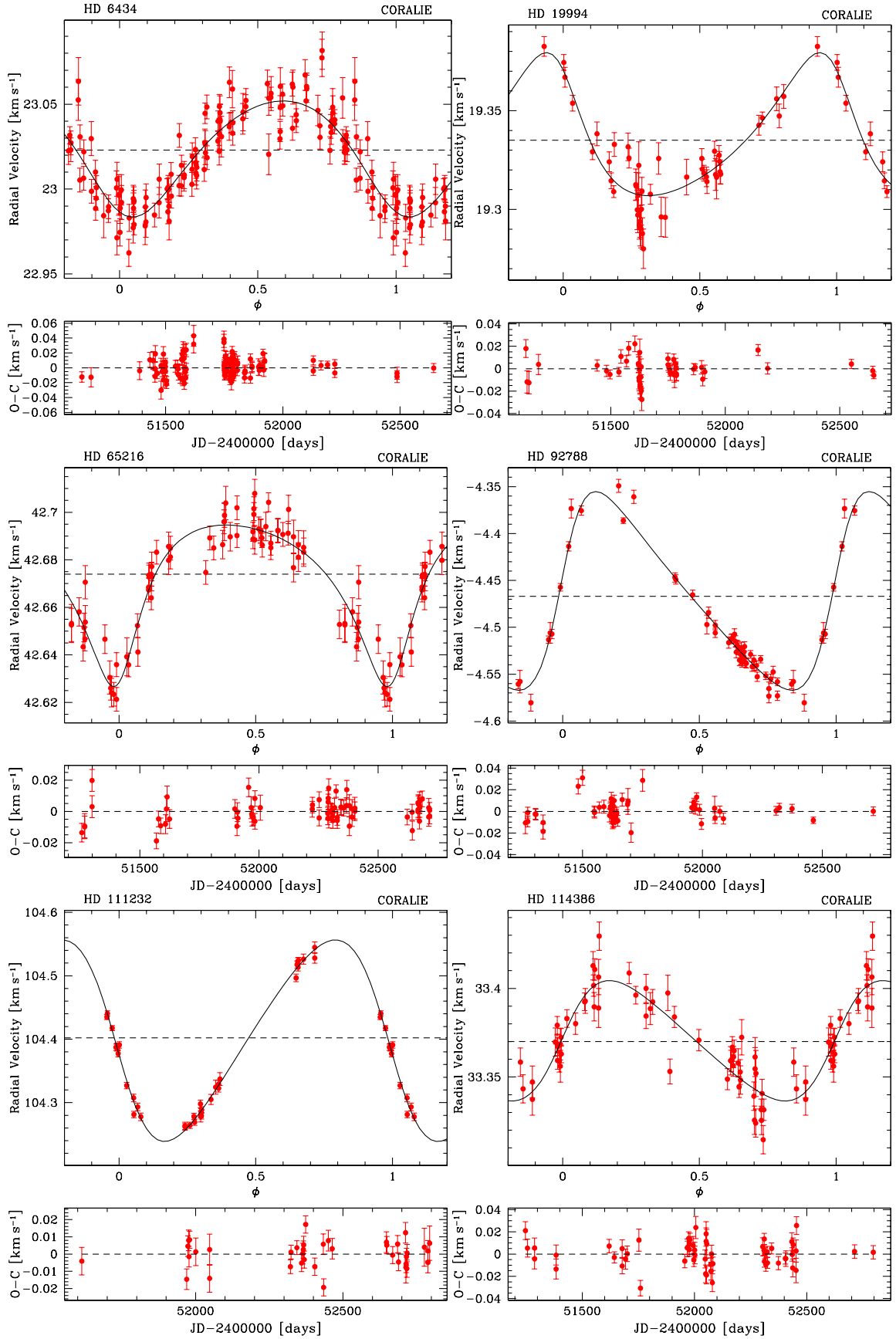


Fig. 2. Phase-folded radial-velocity measurements obtained with CORALIE for HD 6434, HD 19994, HD 65216, HD 92788, HD 111232 and HD 114386, superimposed on the best Keplerian planetary solution (top panel in each diagram). The residuals as a function of Julian Date are displayed in the lower panels.

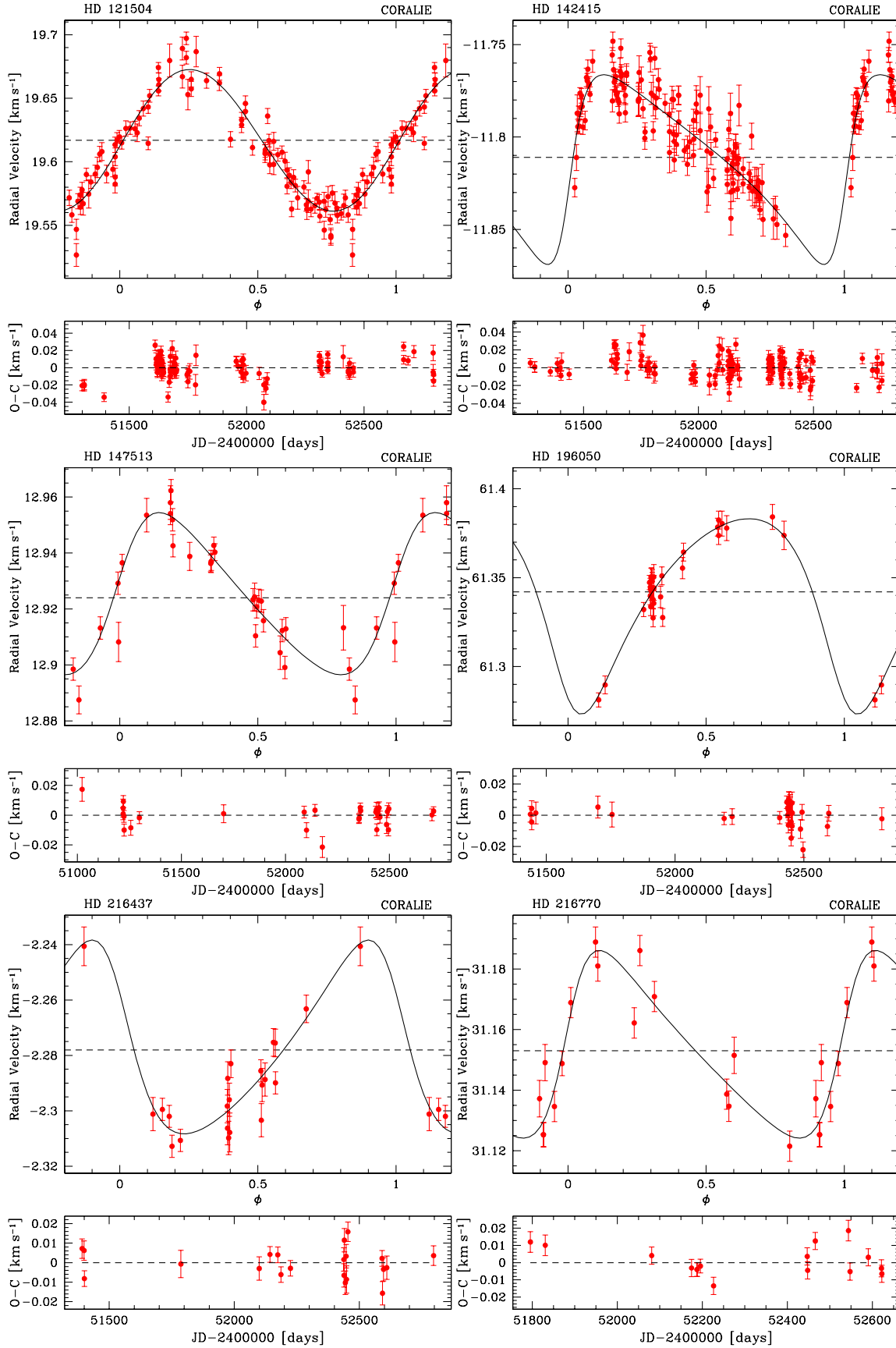


Fig. 3. Phase-folded radial-velocity measurements obtained with CORALIE for HD 121504, HD 142415, HD 147513, HD 196050, HD 216437 and HD 216770, superimposed on the best Keplerian planetary solution (top panel in each diagram). The residuals as a function of Julian Date are displayed in the lower panels.

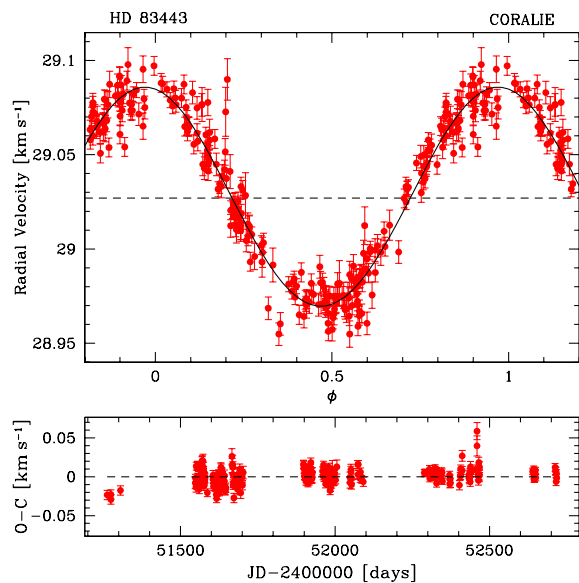


Fig. 4. Phase-folded radial-velocity measurements obtained with CORALIE for HD 83443, superimposed to the best Keplerian planetary solution (top). The residuals as a function of Julian Date are displayed in the lower panel.

Fourier analysis, for additional periodicities in the residuals around the derived solutions. Nothing significant was found for these candidates. Some of them deserve, however, further comments (see the following subsections).

Amongst the 13 single-planet systems presented in this subsection, 10 (HD 19994, HD 65216, HD 92788, HD 111232, HD 114386, HD 142415, HD 147513, HD 196050, HD 216437, HD 216770) are on intermediate or long-period orbits ($100 < P \leq 1350$ days) with medium eccentricities ($0.2 \leq e \leq 0.5$). Such properties are shared by the bulk of the presently known exoplanets⁵. The remaining 3 shorter-period planets (HD 6434, HD 83443, HD 121504) present, on the other hand, a lower eccentricity. The eccentricity-period trend is also observed for stellar binaries. This similitude between the two populations was often brought up as a question for different planet and binary formations. Nevertheless, clear differences exist (see e.g. Mayor & Udry 2000; Halbwachs et al. 2003, for a more complete discussion). Also the mass-period relation of exoplanets, checked for statistical significance by Zucker & Mazeh (2002) and further discussed in Udry et al. (2003d), is apparent in our subsample; the two shortest-period systems host (by far) the lightest planets, with minimum masses below $0.4 M_{\text{Jup}}$, whereas the longest periods ($P \geq 1000$ d) are associated with planet minimum masses of 1.82, 3.02 and $6.8 M_{\text{Jup}}$.

Comments on HD 6434

Since the discovery of the planet, we have doubled the number of measurements available for HD 6434, gathering a total

⁵ Long-period candidates on low-eccentricity orbits (closer to the giant planets in our solar system) are however more and more often discovered as the time coverage of the radial-velocity surveys increases.

of 130 good spectra over more than 1500 days. The star relative faintness and low metallicity lead to a typical radial-velocity photon-noise uncertainty on individual measurements of only $\sim 8 \text{ m s}^{-1}$. However, the large number of measurements allows us to derive precise Keplerian orbital elements for the system (Table 2). The very low planet minimum mass inferred from the orbital solution ($m_2 \sin i = 0.39 M_{\text{Jup}}$) gives us a first example of a very light planet orbiting a deficient star.

Although the star is found to be neither active nor rapidly rotating, a concern is brought by the not so different values of the rotational period (18.6 day) estimated from the activity indicator and the orbital period (22 day). The uncertainty on the orbital period is very small, but the calibrated P_{rot} carries an intrinsic uncertainty. The a posteriori verification that the shape of the spectral lines, estimated by the bisector inverse slope of our cross-correlation functions (BIS; Queloz et al. 2001a), does not vary with the radial velocity provides an indication against activity to be the source of the observed radial-velocity variation. The BIS itself is even constant with a rms of 8.6 m s^{-1} , at the photon-noise level. Moreover, the radial-velocity variation is stable over more than 68 cycles. However, rough simulations by Santos et al. (2003c) raised the possibility of radial-velocity variations without noticeable change in the BIS for slowly rotating stars. In such cases, only simultaneous velocity and photometric measurements can trace the intrinsic origin of the radial-velocity variations, as e.g. for HD 192263 (Santos et al. 2003c) or for the HD 73256 residuals (Udry et al. 2003c). No indication of a 22-d periodicity is present in the Hipparcos photometric data for HD 6434 and the Geneva photometry finds the star stable at a 3 mmag level.

Comments on HD 19994

The residuals around the Keplerian solution (8.1 m s^{-1}) are slightly larger than individual photon-noise errors (median at 6 m s^{-1}). They seem mainly due to velocities around $\text{JD} = 2\,451\,600$ presenting a large dispersion. Taking into account the fairly large rotation of the star and its binarity status, this could possibly come from an enhanced stellar activity level at that moment, although the BIS parameter does not show anything special at that time. Nothing else particular is visible in the residuals.

Comments on HD 83443

HD 83443 was first announced at the Manchester IAU Symp. 202 to host a resonant 2-planet system with periods $P_1 = 2.985 \text{ d}$ and $P_2 = 29.85 \text{ d}$ (Mayor et al. 2000). At that time the available 93 high-S/N CORALIE spectra allowed us to clearly find the 2 periods of variation. The two periodic signals were highly significant. In particular, the false alarm probability for the 30-d period in the data was very low ($\leq 9 \times 10^{-4}$), close to the 4σ detection limit (Fig. 5, top). Moreover, these periodicities were not present in the velocities of contemporary observed constant stars with similar photometric characteristics (Udry et al. 2002). This rules out instrumental effects as the source of the observed variations. A new reduction of the

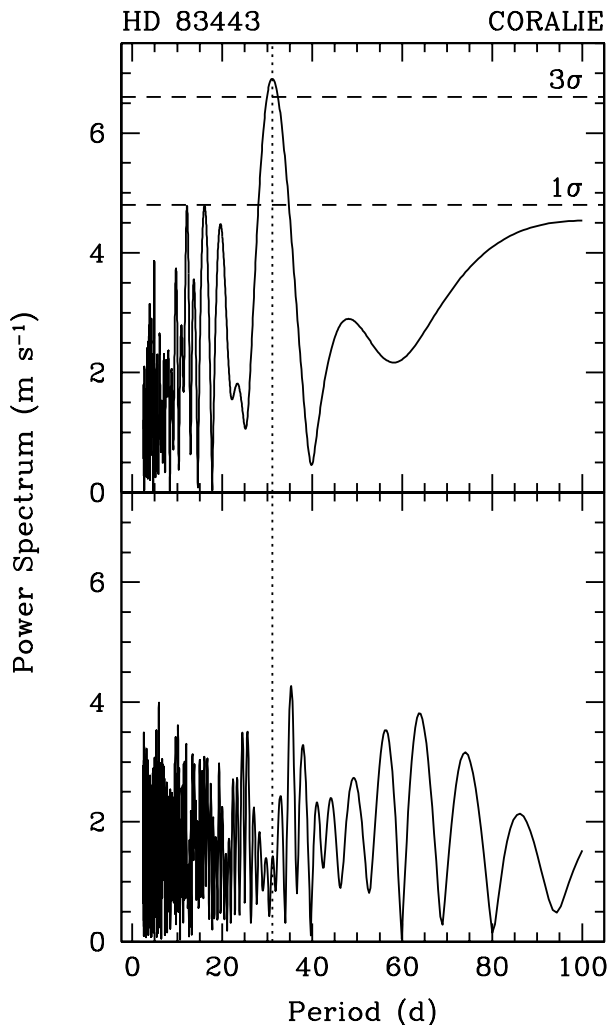


Fig. 5. Fourier transform of the residuals around the 2.98-d orbital solution of HD 83443 b *Top*: for radial-velocities in the $2451\,500 \leq \text{JD} \leq 2451\,702$ period, when the 30-d period signal was seen in the data, and *Bottom*: for later velocities. The false alarm probability of the 30-d period in the early measurements is only 9×10^{-4} (close to the 4σ detection level), whereas the signal has disappeared in the later data.

data using the weighted cross-correlation scheme also confirms the results presented in Manchester.

However, about 2 years later, Butler et al. (2002) trying to confirm the 2-planet system did not detect the 30-d second-planet signal in their Keck+AAT radial-velocity data. We then also verified that it had disappeared in our more recent data as well (Udry et al. 2002). The corresponding peak in the Fourier transform of the radial velocities is no longer present (Fig. 5, bottom).

The origin of this transient signal is not clear yet. An appealing possibility is to attribute the effect to activity as the corresponding period is compatible with the activity-related stellar rotation estimate (within the uncertainties related to the calibration). As mentioned above, we tried for this star as well to see a relation between BIS and the residuals around the 2.98-d Keplerian solution but without success at the precision of our CORALIE data. No 30-d periodicity is found in the BIS data

either. However, if existing, such a relation between residuals and line shape should easily come out of the HARPS data that are already providing a preliminary *commissioning* orbital solution for HD 83443 at a $\sim 1.5 \text{ m s}^{-1}$ precision level (Mayor 2003).

Looking at the orbital solution given in Table 2, we can note that the eccentricity derived for the planet is not significantly different from 0.

With its 2.98-day period, HD 83443 b was a good candidate for photometric transit search. The photometric *uvby* observations were obtained with the *Strömgren Automatic Telescope* (SAT) at ESO La Silla, Chile (Olsen et al. in prep.). Unfortunately, no transit was detected.

Comments on HD 121504

We mentioned above that the somewhat large residuals obtained for this system may probably be related to the stellar activity-induced jitter ($\log R'_{\text{HK}} = -4.57$). We also could see in the temporal distribution of the residuals some indications of an additional radial-velocity drift. If real, this drift is very small. A combined Keplerian + linear drift model yields a drift value of $\sim 3 \text{ m s}^{-1} \text{ y}^{-1}$, without changing noticeably the planetary orbital parameters. Furthermore, the combined fit does not improve much the quality of the solution: the $\sigma(\text{O-C})$ decreases only from 11.6 to 11.2 m s^{-1} . The drift is thus not considered as significant and not included in the solution given in Table 2. Future measurements will confirm or rule out this potential drift.

Comments on HD 142415

The Keplerian solution derived for HD 142415 yields a period of 386.3 ± 1.6 days, not too far from 1 year. As we have points covering the maximum and close (on both sides) to the minimum of the phased radial-velocity curve over 4 full cycles, this proximity to an annual variation is not so much of a concern for the reality of the planetary signal. The trouble resides rather in the difficulty of covering the whole phase interval. As a result the minimum of the curve is highly undersampled and the best fitted orbital solution tends to be very eccentric, increasing the radial-velocity semi-amplitude in an artificial way. This effect is even worsened by the stellar activity induced jitter that makes the orbital elements more difficult to determine. We have thus arbitrarily fixed the eccentricity of the solution to $e = 0.5$, a plausible value when looking at the sequence of the radial-velocity measurements. Note, however, that solutions with e between 0.2 and 0.8 would still be acceptable.

Comments on HD 196050

The phase coverage of our 31 CORALIE radial velocities is not good enough to obtain a constrained value of the planet eccentricity. We thus fixed this eccentricity to $e = 0.3$, a value minimizing the residuals around the derived solution.

Table 3. CORALIE simultaneously derived 2-Keplerian orbital solutions as well as inferred planetary parameters for the multi-planet systems HD 82943 and HD 169830. Parameter definitions are the same as in Table 2. Note that for HD 82943, the e and ω elements are not well defined in the sense that there exist other solutions with very different e and ω estimates but with equivalent $\sigma(\text{O-C})$ values (see text).

Parameter		HD 82943 c	HD 82943 b	HD 169830 b	HD 169830 c
		(HIP 47007)		(HIP 90485)	
<i>Det.Ref.</i>		ESO (May 2000); ESO (April 2001)		Naef et al. (2001); Udry et al. (2003b)	
P	[days]	219.4 ± 0.2	435.1 ± 1.4	225.62 ± 0.22	2102 ± 264
T	[JD-2 400 000]	52284 ± 1	51758 ± 13	51923 ± 1	52516 ± 25
e		0.38 ± 0.01	0.18 ± 0.04	0.31 ± 0.01	0.33 ± 0.02
V	[km s^{-1}]	8.144 ± 0.001		-17.209 ± 0.006	
ω	[deg]	124 ± 3	237 ± 13	148 ± 2	252 ± 8
K	[m s^{-1}]	61.5 ± 1.7	45.8 ± 1.0	80.7 ± 0.9	54.3 ± 3.6
$a_1 \sin i$	[10^{-3} AU]	1.145	1.801	1.591	9.898
$f(m)$	[$10^{-9} M_{\odot}$]	4.156	4.118	10.56	29.27
$m_2 \sin i$	[M_{Jup}]	1.85	1.84	2.88	4.04
a	[AU]	0.75	1.18	0.81	3.60
N_{meas}		142		112	
<i>Span</i>	[days]	1593		1506	
$\sigma(\text{O-C})$	[m s^{-1}]	6.8		8.9	
<i>mask</i>		weighted K0		weighted K0	

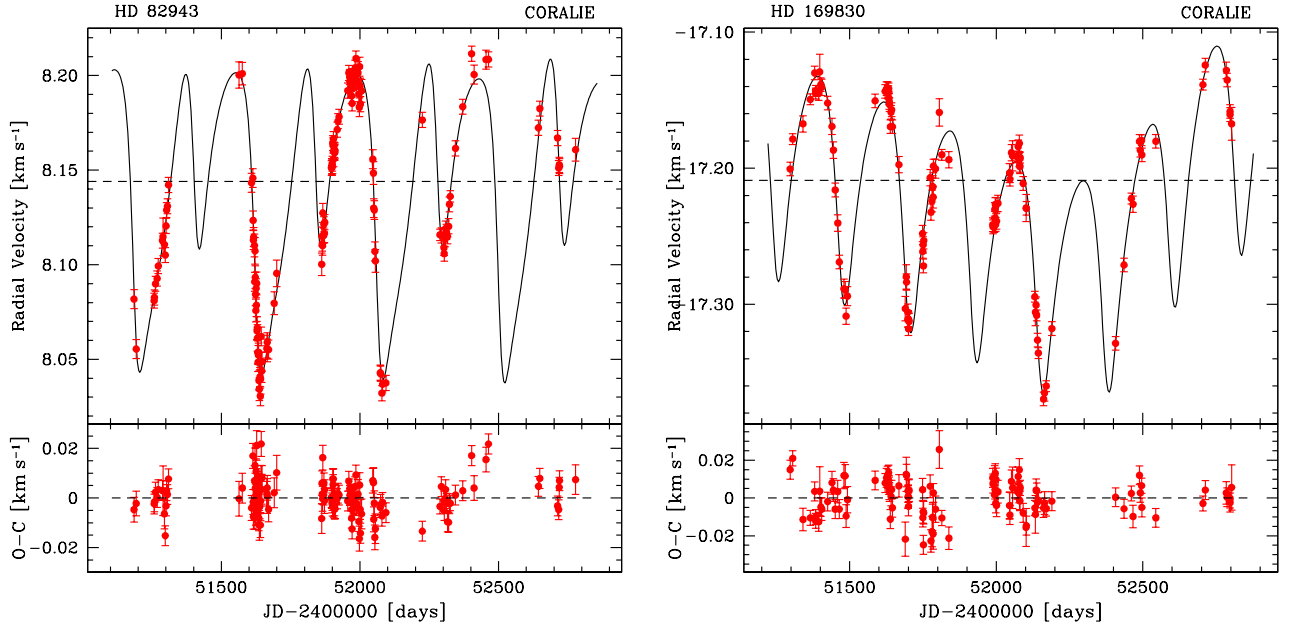


Fig. 6. *Top:* temporal radial-velocity measurements obtained with CORALIE for the 2-planet systems HD 82943 (left) and HD 169830 (right), superimposed to the best simultaneously-derived 2-Keplerian planetary solutions. *Bottom:* residuals as a function of Julian Date.

3.2. The 2-planet systems

3.2.1. The 2-planet resonant system around HD 82943

The star hosts a very interesting 2-planet system. Between $\text{JD} = 2\,451\,184$ and $\text{JD} = 2\,452\,777$, we have gathered 142 good CORALIE spectra of the star that allow us to derive a 2-Keplerian approximate solution with periods $P_b = 435.1\text{d}$ and $P_c = 219.4\text{d}$. The whole set of orbital parameters are given in Table 3 and the solution and velocities are displayed in Fig. 6 (left). The particular values of the periods made us miss the short-period minimum of the curve when the star was behind the Sun. The long-period planet (HD 82943 b) was thus

announced first (ESO 2000), about 1 year before the detection of the secondary planet signature (HD 82943 c; ESO 2001).

The $P_i/P_j = 2/1$ resonant systems are very important because, when the planet orbital separations are not too large, planet-planet gravitational interactions become non-negligible during planet “close” encounters, and will noticeably influence the system evolution on a timescale of the order of a few times the long period. The radial-velocity variations of the central star will then differ substantially from velocity variations derived assuming the planets are executing independent Keplerian motions. We observe a temporal variation of the *instantaneous* orbital elements. In the most favourable cases, the orbital-plane inclinations, not otherwise known from the radial-velocity technique, can be determined since the

amplitude of the planet-planet interaction directly scales with their true masses.

In the case of multiple planets, only approximate analytic solutions of the gravitational equations of motion exist, and one must resort to numerical integrations to model the data. Several studies have been conducted in this direction for the Gl 876 system (Laughlin & Chambers 2001; Rivera & Lissauer 2001; Nauenberg 2002), similar to HD 82943 in the sense that it also hosts two 2/1 resonant planets at fairly small separations. The results of the *Newtonian* modeling of the Gl 876 system have validated the method, improving notably the determination of the planetary orbital elements, but the time coverage of the measurements is still too small for the method to provide strong constraints on the plane inclinations. The valley of the acceptable solutions is still very shallow, although including the correct answer provided by *HST* astrometric observations (Benedict et al. 2002). Further radial-velocity measurements will undoubtedly improve the situation.

Our correct modeling of HD 82943, taking into account the planet-planet interactions, is under study and will be presented in a forthcoming paper with a more detailed description of the system behaviour (Correia et al. in prep.).

Our present approximate solution for the system (Table 3) yields residuals at the level of the photon noise of the radial-velocity measurements. The inferred two planetary masses are very similar. Although in a 2/1 resonance, the two orbits do not seem to be aligned. However, we have to warn the reader not to take too literally the results described here because:

- As mentioned above, due to the planet-planet interactions, the orbital elements are time dependent;
- Due to the non-optimum phase coverage, the planet eccentricities and ω s are badly (if at all) constrained by the data. The small uncertainties given in the table only relate to the given local solution in parameter space. There are, however, other local solutions with almost equivalent χ^2 minimum values. For instance, a solution with the very different values of the eccentricities $e_c = 0.4$ and $e_b \simeq 0$ only increases the residuals from 6.8 to 6.9 m s^{-1} . In this case, as $e_b \simeq 0$, ω_b is completely non-determined and it is then possible to find for these eccentricities an aligned configuration with $\omega_b = \omega_c = 110$ deg and the same level of residuals (6.9 m s^{-1}), leaving furthermore P_i and K_i almost unchanged.

We will now continue to follow closely this system, accumulating measurements to improve in the future the derived solution.

3.2.2. The HD 169830 hierarchical 2-planet system

A 230-d period planet orbiting HD 169830 was first described in Naef et al. (2001). The orbital solution was derived from the 35 CORALIE spectra available at that time. After the second maximum of the radial-velocity curve, we noticed an additional trend in the data pushing us to follow the star more closely. We have now gathered 112 good spectra that allow us to simultaneously derive a complete 2-Keplerian orbital solution for the system (Table 3 and Fig. 6, right).

Unlike HD 82943, this system is not resonant but more hierarchically structured. The separation between the 2 planets stays always fairly large, the 2-Keplerian model is then supposed to provide a good approximation of the system evolution on a fairly long time. However, the time span of our velocity measurements barely covers the long period variation. The corresponding planetary orbit is thus not completely constrained and a large uncertainty is still observed for the long period.

This 2-planet system is the first to be announced after the proposition by Mazeh & Zucker (2003b) of a possible correlation between mass ratio and period ratio for adjacent planets in multi-planet systems. It is interesting to note that the new system agrees with the proposed correlation (Mazeh & Zucker 2003a).

4. Summary

We have described in this paper 16 still unpublished exoplanet candidates discovered with the CORALIE echelle spectrograph mounted on the 1.2-m Euler Swiss telescope at La Silla Observatory. Amongst these new candidates:

- Ten are typical extrasolar Jupiter-like planets on intermediate- or long-period ($100 < P \leq 1350$ d) and fairly eccentric ($0.2 \leq e \leq 0.5$) orbits (HD 19994, HD 65216, HD 92788, HD 111232, HD 114386, HD 142415, HD 147513, HD 196050, HD 216437, HD 216770). They resemble the bulk of extra-solar planets found to date.
- Two of these planets (HD 19994, HD 147513) are orbiting one component of a multiple-star system. Such planets seem to present different orbital and mass characteristics than the other *single*-star planets (Zucker & Mazeh 2002; Eggenberger et al. 2003). The companion to HD 147513 is even a white dwarf, the evolution to which has probably also influenced the planet evolution through mass transfer between the two stars.
- Three candidates are shorter-period planets (HD 6434, HD 121504, HD 83443) with lower eccentricities (the latter being a hot Jupiter).
- More interesting cases are given by the multiple-planet systems HD 82943 and HD 169830. HD 82943 is a resonant $P_b/P_c = 2/1$ system in which planet-planet interactions are influencing the system evolution. HD 169830 is non-resonant and more hierarchically structured, and therefore less affected by this kind of interaction.

From a more global point of view, our candidates follow the period-eccentricity and period-mass trends observed for the whole sample of known extra-solar planets. They follow as well the trend for stars hosting planets to be more metal rich than *normal* stars of the solar neighbourhood (Santos et al. 2001, 2003b; Gonzalez et al. 2001; Laws et al. 2003). Only 3 amongst the 15 stars are metal deficient with regards to the Sun whereas almost all the others present high [Fe/H] values.

We emphasize the difficulty encountered to fully constrain multi-planet systems. Such a task, involving many free parameters, requires a good phase coverage and a fair number of measurements, even for the simplest cases. As a consequence, studies on multi-planet system stability should not rely too closely on the given orbital parameters. The published solutions will probably change in the future (some will notably change) as

more measurements become available. A substantial advance in this domain will be brought by the the new HARPS spectrograph mounted on the ESO 3.6-m telescope at La Silla (Pepe et al. 2002b) available since October 2003. With the very high precision achieved for radial-velocity measurements and the quality of the spectra, HARPS is now providing us with an unequalled tool to characterize multi-planet systems and/or disentangle activity-induced jitter from orbital radial-velocity variations.

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