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The CORALIE survey for southern extra-solar planets

II. The short-period planetary companions to HD 75289 and HD 130322*

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Abstract. Doppler measurements from the high-resolution CORALIE spectrometer of the stars HD 75289 and HD 130322 reveal 2 new extra-solar giant planets. They are the second and third planetary candidates discovered with CORALIE in less than 1 year, since its installation on the 1.2-m Euler Swiss telescope at La Silla. The minimum mass of the planet around HD 75289 ($m_2 \sin i = 0.42\,\mathrm{M_{Jup}}$) is the lightest found to date for a solar-type star companion. The orbital period is 3.5 days and the orbit is circular. The second candidate, a Jupiter-mass planet, orbits HD 130322 in 10.72 days, on an almost circular trajectory. Due to their small orbital periods, both planets belong to the hot Jupiter family, increasing thus the already large number of known Jupiter sized planets with orbits much smaller than in the solar system.

Key words: techniques: radial velocities – binaries: spectroscopic – stars: individual: HD 75289 – stars: individual: HD 130322 – stars: activity – planetary systems

1. Introduction

After the discovery of the first extra-solar planet orbiting the solar twin star 51 Peg by Mayor & Queloz (1995), more than 25 planetary candidates including a 3-planet system (Butler et al. 1999) have now been indirectly detected by high-precision radial-velocity monitoring of solar-type stars of the solar neighbourhood (see Marcy et al. 1999 (MCM99); Queloz et al. 2000 and Vogt et al. 2000 for recent reference updates). The unexpected characteristics of several of the new systems (small separations, large eccentricities, etc), have challenged our conventional views on planetary formation. Amongst the most interesting problems is the open question of the formation of hot Jupiters, giant planets very close to their parent stars. Several scenarios are competing to explain these systems. In the continuation of the conventional picture requiring the presence of an "ice" core for the runaway growth of giant planets in the outer regions of the protostellar nebulae (Pollack & Bodenheimer 1989; Boss 1995; Lissauer 1995), a first approach invokes an inwards migration motion of the forming planet due to planet-disk interactions (Goldreich & Tremaine 1980; Lin & Papaloizou 1986; Ward 1997) which stops because of star-planet tidal interactions, mass transfer from the planet to the star (Lin et al. 1996; Trilling et al. 1998) or lack of material in the very inner region of the system (magnetospheric cavity). Other scenarios involving gravity interactions between giant planets (Weidenschilling & Marzari 1996; Rasio & Ford 1996) were also proposed to bring outer giant planets close to their stars. Another recent approach based on in situ formation (Wuchterl 1996, 1997, 1999; Bodenheimer et al. 1999) is gathering an increasing support.

In this context, the future statistical improvements expected from ongoing large surveys will prove to be decisive. Among the latter, our ambitious planet-search programme with the CORALIE echelle spectrograph on the 1.2-m Euler Swiss telescope at La Silla (Chile) is briefly described in the next section. The results from this long-term systematic survey will be presented in a series of numbered publications directly following new extra-solar planet discoveries, so that complementary studies like detailed abundance analyses, photometric transit or dust disk searches can be undertaken rapidly. Within about one year the CORALIE spectrograph has already made a decisive contribution to the discovery of the planetary companion around the M4 dwarf Gl 876 (Delfosse et al. 1998; simultaneously discovered by Marcy et al. 1998) and allowed us to detect 3 extra-solar planets: the companion of Gl 86 described in Queloz et al. (2000, Paper I) and the two new candidates presented in this paper, namely those around HD 75289, the lightest extra-solar planet found to date around a solar-type star, and HD 130322. During the preparation of this publication, a new CORALIE planetary candidate was announced around the star HD 192263 (Santos et al. 1999a). It is described in details in Santos et al. (2000, Paper III).

With periods of 3.51 and 10.72 days, respectively, the planets presented here belong to the hot Jupiter family and thus

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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

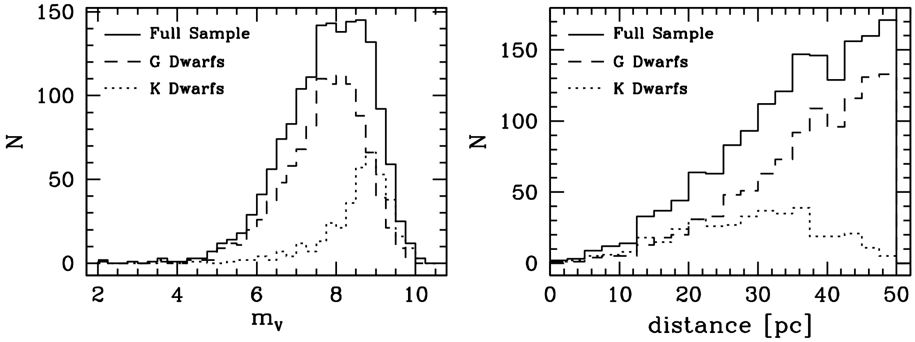

Fig. 1. Apparent magnitude and distance distributions of the CORALIE planet-search sample. 80% of the stars are brighter than $m_V = 9$ the faintest ones being mainly K dwarfs for which our technique is the most efficient

increase the number of planets with small orbital separations, an accumulation in the distribution that, although favoured by observational biases, is nevertheless statistically significant (MCM99).

The parent star descriptions, radial-velocity observations, orbital solutions and inferred planetary characteristics for these two new candidates are presented in Sects. 3 and 4, respectively. Individual radial-velocity measurements will be made available in electronic form at the CDS in Strasbourg. In Sect. 5, we discuss the other sources of possible radial-velocity variations and rule them out by use of bisector analysis and photometry. Finally, Sect. 6 brings a summary of the results and a short discussion.

2. The CORALIE planet-search sample

The diversity of characteristics presented by the new planetary systems (e.g. MCM99) makes clear that existing ideas of planetary formation need serious revision. Enlarging the number of detected systems is now necessary to obtain proper statistical distributions of orbital elements, planetary masses, etc, fundamental for a better understanding of the formation and evolution of these systems.

Since the summer of 1998, a large high-precision radial-velocity programme is being carried out with the CORALIE echelle spectrograph on the 1.2-m Euler Swiss telescope at La Silla. Velocities are measured by numerically cross-correlating high-resolution spectra with a template appropriate for G–K stars. Further information on the method as well as technical and instrumental details and a description of the first discoveries of the programme are given in Baranne et al. (1996) and in Queloz et al. (1999, 2000).

The overall sample consists of about 1650 solar-type stars selected according to distance in order to obtain a well-defined volume-limited set of dwarf stars. As very briefly described in Udry et al. (1999), the global sample selection was performed applying the following criteria:

– Selection of stars closer than 50 pc ($\pi \geq 20$ mas) with precise parallaxes ($\sigma_\pi \leq 5$ mas) and F8 ≤ Spectral type < M1 in the HIPPARCOS catalogue.
– Photometric cut off of giant stars (2.5 mag off a "mean" main sequence). This allows us to remove most evolved stars while keeping stars with misclassified luminosity classes like the two candidates presented here (see below).
– Removal of the fainter cool dwarfs, by a colour-dependent distance cut off ($d_{\rm max} = f(B-V)$), taking into account that our cross-correlation technique needs less signal for K dwarfs[1].

The final sample is presented in Fig. 1 which shows the stellar apparent magnitude and distance distributions. We note that ∼80% of the selected stars are brighter than $m_V = 9$ and that faint objects are mostly K dwarfs for which our technique is the most efficient.

For the planet search itself, large amplitude binaries and potentially intrinsic variable stars (large activity index and fast rotators, Saar et al. 1998, Santos et al. 1999b, see Sect. 5) have to be avoided. The stability of a planetary system may be perturbed and even destroyed by the close proximity of a stellar companion. Moreover, the simultaneous determinations of the large amplitude and planetary orbits would require an additional observational effort. Most large-amplitude systems were detected with the CORAVEL spectrographs (Baranne et al. 1979) at a lower precision level (300m s^{-1}). Long-period binaries showing only linear drifts in radial velocity remain nevertheless good candidates for the planet search as the gravitational perturbation of the stellar companion is weak and the long-period orbital effect on the radial velocities can be easily corrected (e.g. Gl 86, Paper I). The CORAVEL measurements also provide us with the stellar rotational velocity (Benz & Mayor 1984) often used as an activity indicator (Saar et al. 1998). The fast rotators and large amplitude binary systems are collected in low-priority subprogrammes used as observing backup programmes; however, they still belong to the global volume-limited sample to be used for statistical purpose. We are left in the end with about 1000 high-priority candidates for the core of the planet-search programme itself.

The CORALIE survey offers a unique opportunity to explore the relation between activity and other stellar characteristics like rotational velocity, rotational period or intrinsic radial-velocity and photometric variations (Santos et al. 1999b).

Because of its size and the quality of the measurements, the above defined planet-search programme will also significantly improve the data available for stellar binary systems, reactualizing the Duquennoy & Mayor (1991) type of work. In

[1] For a given signal-to-noise ratio, the photon-noise error inversely scales with the depth of the cross-correlation function which is maximum for late K dwarfs with the template used for solar-type stars

particular, the determination of a good distribution of masses of companions of solar-type stars down to the planet regime will bring some further insights in the brown dwarf – planet transition zone. This will further support or invalidate the so-called "brown-dwarf desert" suspected by the lack of brown-dwarf candidates in the high-precision radial-velocity surveys (Marcy & Butler 1995) and recently emphasized by the study of Halbwachs et al. (2000) which combines CORAVEL and ELODIE radial-velocity measurements with HIPPARCOS astrometric data to derive real masses for a set of spectroscopic brown-dwarf candidates (Mayor et al. 1997).

Finally, the survey will naturally provide good candidates for the future ground-based (VLTI) and spatial (SIM) interferometric programmes.

3. A planetary companion around HD 75289. Down towards the mass of Saturn

3.1. Stellar characteristics of HD 75289

HD 75289 (HIP 43177) is a bright ($V = 6.35$) G0 dwarf in the southern Vela (Sail) constellation. The HIPPARCOS catalogue lists a colour index $B - V = 0.578$ and a precise astrometric parallax $\pi = 34.55 \pm 0.56$ mas (ESA 1997) which puts the star at a distance of 29 pc from the Sun. Thus the absolute magnitude $M_V = 4.04$, typical for a G0 dwarf. This invalidates the super-giant classification usually given, for example in the Bright Star Catalogue (Hoffleit & Jaschek 1982).

This discrepancy was already pointed out in Gratton et al. (1989) who defined the star to be a "nearby metal-rich small-mass dwarf near the turn off". In their high-resolution spectroscopic analysis they derived a gravity $\log\,g = 3.8$ from the ionization equilibrium and an effective temperature $T_{\rm eff} = 6000$ K from the excitation equilibrium of the Fe I absorption lines. The latter is in good agreement with $T^G_{\rm eff} = 5982$ K derived from the Geneva photometry (Grenon 1981, private communication). From their individual line abundance measurements, Gratton et al. also estimate a metallicity index [A/H] = 0.2 in agreement with the [M/H] = 0.28 value from the Geneva photometry and with the [Fe/H] = 0.29 value derived from the calibration of the surface of the CORAVEL cross-correlation dip (Pont 1997). This metallicity is higher than the average value (slightly negative) of the metallicity of the stars in the CORALIE sample, as is the case for most of the other stars with giant planets.

Using a bolometric correction $BC = -0.0488$ (Flower 1996[2]), the star luminosity is estimated to be $L = 1.99\,{\rm L}_\odot$. According to the evolutionary tracks of the Geneva evolution models with appropriate metal abundance (Schaerer et al. 1993), the position of the star in the HR diagram indicates an age comparable to the age of the Sun (but with large uncertainties) and a mass $M = 1.15\,M_\odot$. The derived mass is slightly higher than the typical mass of G0 dwarfs because of the high metallicity of the star.

[2] Quoted values in the paper include errors. The correct values have been obtained directly from the author

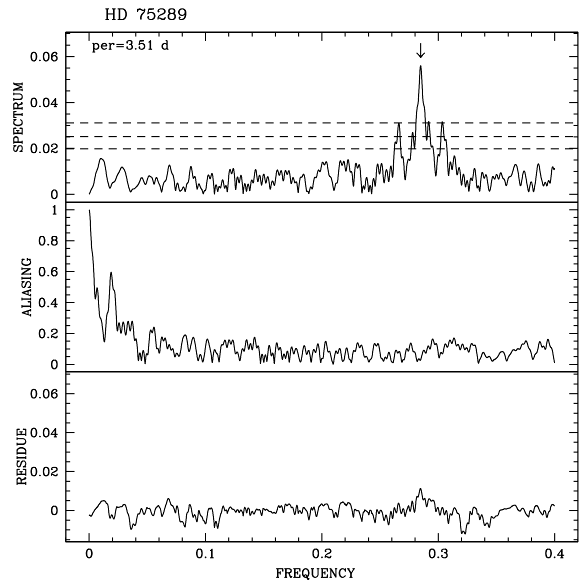

Fig. 2. Fourier power spectrum of the radial-velocity measurements (upper panel) for HD 75289. The middle panel gives the alias spectrum due to the data sampling (Deeming method) and the lower panel the residue after removing the contribution of the main peak and its aliases. The 3.5-d periodicity is obvious in the velocity data (mean peak and aliases). In the upper panel, horizontal lines represent (from bottom to top) 0.5, 0.05 and 0.001 false-alarm probabilities

From the emission flux in the middle of the Ca II H line after correction for the photospheric flux, we obtain the chromospheric activity indicators $S_{COR} = 0.159 \pm 0.009$ and $\log{(R'_{HK})} = -4.96$ (Santos et al. 1999b), very close to $S = 0.154$ and $\log{(R'_{HK})} = -5.0$ given in Henry et al. (1996). These values are typical for stars with low chromospheric activity level (Henry et al. 1996). From the calibration of Donahue (1993) also quoted in Henry et al. (1996), they lead to an age estimate of 5.6 Gyr compatible with the age derived from the evolutionary tracks (large uncertainties in both determinations).

Observed and inferred stellar parameters are summarized in Table 1 with the references of the corresponding observations or methods used to derived the interesting quantities.

3.2. CORALIE orbital solution for HD 75289

Between November 1998[3] and October 1999 we obtained 88 precise radial velocities of HD 75289. The distribution of the photon-noise errors of individual measurements (ε_i) peaks around 4.5 m s^{-1} with a mean value $<\varepsilon_i> = 5.5$ m s^{-1}. A Fourier transform (using the approach by Deeming (1975, 1976)) of the temporal data exhibits a strong periodic signal around $P = 3.5$ days, as shown in Fig. 2 (upper panel). Horizontally-dashed lines in the figure represent 0.5, 0.05 and 0.001 false-alarm probabilities derived from Monte-Carlo random realisations with the same temporal sampling and r.m.s. as the real data. The significant secondary peaks are aliases as indicated by the aliasing and residue windows in the figure

[3] The discovery was announced beginning of February 1999

Table 1. Observed and inferred stellar parameters for HD 75289 and HD 130322 with the corresponding references

Parameter		**HD 75289**	**HD 130322**	References
Spectral Type		G0	K0	HIPPARCOS
V		6.35	8.04	HIPPARCOS
$B-V$		0.578	0.781	HIPPARCOS
π	[mas]	34.55 ± 0.56	33.6 ± 1.5	HIPPARCOS
M_V		4.04	5.67	
$L/L_\odot$		1.99	0.50	Flower (1996)
$[Fe/H]$		0.29	-0.02	CORAVEL, Pont (1997)
$[M/H]$		0.28 ± 0.02	0.1 ± 0.04	Geneva photometry
$M/M_\odot$		1.15	0.79	Geneva models, Schaerer et al. (1993)
$T_{\rm eff}$	[K]	6000	5330	Gratton et al. (1989), Flower (1996)
$T^G_{\rm eff}$	[K]	5982	5318	Geneva photometry
$v \sin i$	[km s^{-1}]	4.37 ± 1	1.9 ± 1.2	CORAVEL, Benz & Mayor (1984)
$\log(R'_{HK})$		-4.96	-4.39	Santos et al. (1999b)
$P_{\rm rot}(R'_{HK})$	[days]	15.95	8.7	Noyes et al. (1984)
age(R'_{HK})	[Gyr]	5.6	0.35	Donahue (1993), Henry et al. (1996)

Table 2. CORALIE best Keplerian orbital solutions derived for HD 75289 and HD 130322 and inferred planetary parameters. For HD 75289, the eccentricity is not significant according to the Lucy & Sweeney (1971) test and we thus also provide the circular orbital solution

Parameter		**HD 75289**	**HD 75289 (e=0)**	**HD 130322**
P	[days]	3.5098 ± 0.0007	3.5097 ± 0.0007	10.720 ± 0.007
T	[JD-2400000]	51355.91 ± 0.48	51355.41 ± 0.03	51287.38 ± 0.68
e		0.024 ± 0.021	0	0.044 ± 0.018
V	[km s^{-1}]	9.258 ± 0.001	9.258 ± 0.001	-12.504 ± 0.002
ω	[deg]	50.16 ± 49.17	0	203.63 ± 23.14
K	[m s^{-1}]	54 ± 1	54 ± 1	115 ± 2
$N_{\rm mes}$		88	88	118
$\sigma(O-C)$	[m s^{-1}]	7.47	7.44	15.4
$a_1 \sin i$	[Mm]	2.602 ± 0.054	2.603 ± 0.054	16.916 ± 0.308
$f(m)$	[10^{-9} M$_\odot$]	$5.713 \cdot 10^{-2} \pm 0.356 \cdot 10^{-2}$	$5.716 \cdot 10^{-2} \pm 0.354 \cdot 10^{-2}$	1.682 ± 0.092
m_1	[M$_\odot$]	1.15	$\pm$	0.79
$m_2 \sin i$	[M$_{\rm Jup}$]	0.42	$\pm$	1.02
a	[AU]	0.046	$\pm$	0.088
$T_{\rm eq}$	[K]	1260		720

(lower panels). The best-fit Keplerian model (Fig. 3) yields an accurately constrained orbital period of 3.5098 ± 0.0007 days, a very small eccentricity $e = 0.024 \pm 0.021$, compatible with a circular orbit according to the Lucy & Sweeney (1971) test at a 92% confidence level, and a semi-amplitude $K = 54 \pm 1$ m s^{-1} of radial-velocity variation. At such a small distance from its parent star and following Guillot et al. (1996), the planet equilibrium temperature at the surface is estimated to be around 1260 K. The complete set of orbital elements with their uncertainties are given in Table 2 for the circular and "eccentric" solutions.

Using the previously derived 1.15 M$_\odot$ mass for HD 75289, the best-fit orbital parameters imply a companion minimum mass $m_2 \sin i = 0.42$ M$_{\rm Jup}$ and a separation $a = 0.046$ AU between the star and the planet. The inferred planetary minimum mass corresponds to 1.4 times the mass of Saturn and is the lightest found to date for an extra-solar planet around a solar-type star. Despite the low mass of the planet, the velocity variation is accurately determined and the error on the minimum mass (without taking into account the uncertainty in the primary mass estimate) is less than 2%.

From the relation between the activity index and stellar rotation period (Noyes et al. 1984) we derive a period $P_{\rm rot}$ = 16 days for HD 75289. Assuming that the orbital and rotation axes coincide, a "statistical" equatorial velocity $V_{\rm eq}$ may be derived from the star radius and then the orbital plane inclination is obtained from the measured projected rotational velocity $v \sin i = 4.37 \pm 1$ km s^{-1} (calibrated from the width of the CORAVEL cross-correlation dip; Benz & Mayor 1984). Using the simple relation between stellar luminosity, radius and effective temperature $L = 4\pi R^2 \sigma T^4_{\rm eff}$ and with the stellar parameter values given above, the radius is estimated to be ~ 1.4 R$_\odot$, slightly larger than the typical radius for a G0 dwarf with solar metallicity. This leads to a value $V_{\rm eq} \simeq 4.4$ km s^{-1} very close to the quoted $v \sin i$. Taking into account the uncertainty on $v \sin i$, a maximum mass of 0.51 M$_{\rm Jup}$ is estimated for the planet.

The r.m.s. to the Keplerian fit is 7.5 m s^{-1}, similar to the velocity r.m.s. for the orbital fit of the previously-discovered

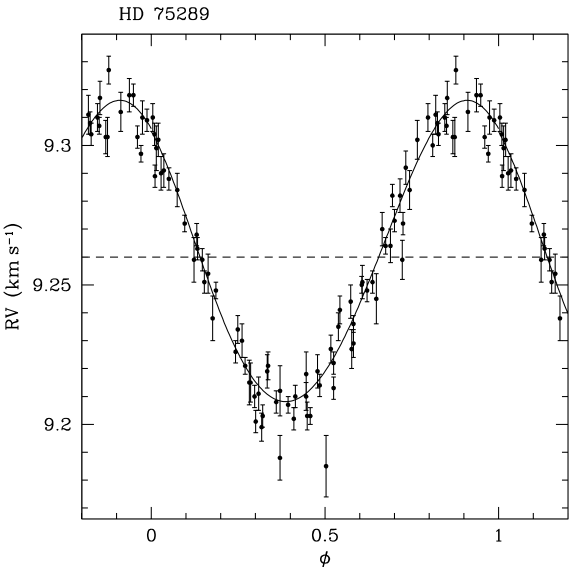

Fig. 3. Phase-folded radial-velocity measurements obtained with CORALIE for HD 75289. Error bars represent photon-noise errors

CORALIE planet around Gl 86 (Paper I). The residuals around the solution show no evidence of a possible additional companion on a short- or intermediate-period orbit.

A set of 5 CORAVEL radial-velocity measurements of HD 75289 obtained over slightly less than 14 years, between 1983 and 1997, present a dispersion of $250\,\mathrm{m\,s^{-1}}$, the level of precision of CORAVEL. Older measurements from the literature (Gratton et al. 1989, Parsons 1983, Catchpole et al. 1982, Przybylski & Kennedy 1965) do not show any clear evidence of radial-velocity variation. We thus conclude that HD 75289 is very probably a single star contrarily to the "potential binary" characteristics reported in the literature.

3.3. Transit candidate

The discovery of hot Jupiters has major theoretical and practical implications. For favourable inclination (edge-on orbital plane), high-accuracy photometric eclipse observations become possible. The transit light curve provides the inclination angle and the radius of the transiting body (using the on-transit and off-transit flux ratio). The probability of such a transit is proportional to $(R_\star + R_p)/a$ (stellar radius over star-planet separation, e.g. Borucki & Summers 1984) and is typically about 10% for a hot Jupiter on a 4-day orbit. Combining the photometric data of a detected transit with radial-velocity measurements it then becomes possible to determine the real mass of the companion and therefore to determine the nature of the transiting body. Finally, from the real mass and radius, we get the mean density of the companion, bringing thus strong constraints to theories of planet and brown-dwarf formation and atmosphere models. Such an observation would also represent a direct detection of an extra-solar planet.

With its 3.5-day period, the HD 75289 system is a good transit candidate. Furthermore, as discussed above, a favourable geometry could be expected from activity indicator and rotational velocity considerations. During the winter 1998–1999, an intensive campaign of high-precision relative photometry has been initiated on the 50-cm Danish telescope at La Silla in order to detect a possible transit. Future results of this ongoing monitoring will be described in details in a coming paper (Santos et al., in prep). Up to now the photometric measurements have already demonstrated the luminosity stability of the star at a few millimagnitude level.

During the preparation of this paper, a planetary companion transiting in front of the star HD 209458 was independently observed by Charbonneau et al. (2000; two transits in September 1999) and Henry et al. (2000; in November 1999).

4. HD 130322. The third CORALIE candidate

4.1. Stellar characteristics of HD 130322

HD 130322 (HIP 72339) is a K0 dwarf with $V = 8.04$ and $B - V = 0.781$. The HIPPARCOS catalogue (ESA 1997) lists a precise astrometric parallax $\pi = 33.6 \pm 1.5$ mas or a distance of 29.76 pc from the Sun. The derived absolute magnitude $M_V = 5.67$ invalidates the commonly given giant classification.

No detailed LTE spectroscopic analysis of HD 130322 has been carried out to our knowledge. The only reference attaches HD 130322 to the Strömgren photometry of the large sample studied by Olsen (1993). From the $b - y = 0.475$ value the Olsen (1984) calibration yields $T_{\rm eff} = 5321$ K and with the Schuster & Nissen (1989) calibration we derive [Fe/H] = -0.02. These estimates agree with other determinations given below. Following Flower (1996), we derive $T_{\rm eff} = 5330$ K and $L = 0.5\,\mathrm{L_\odot}$. Calibrations of the CORAVEL cross-correlation function parameters also yield $v \sin i = 1.9 \pm 1.2\,\mathrm{km\,s^{-1}}$ (Benz & Mayor 1984) and [Fe/H] = -0.02 (Pont 1997). Finally, the Geneva photometry corroborates these values by providing [M/H]=0.1 and $T^G_{\rm eff} = 5318$ K (Grenon, private communication).

The fairly large $\log(R'_{HK}) = -4.39$ value derived from the Ca II H core emission (Santos et al. 1999b) points towards a young age for the star: the Donahue (1993) calibration gives an age estimate of about 0.35 Myr. The kinematical characteristics of HD 130322 ($U = -9.5\mathrm{km\,s^{-1}}$, $V = -26.1\,\mathrm{km\,s^{-1}}$, $W = -10.9\,\mathrm{km\,s^{-1}}$, estimated from radial and HIPPARCOS velocities) comparable with the kinematical properties of stars in the Pleiades (Chereul et al. 1999) further support such a young age.

The observed and inferred stellar parameters for HD 130322 are summarized in Table 1.

4.2. CORALIE orbital solution for HD 130322

The set of 118 precise radial velocities obtained from February to August 1999[4] over about 17 cycles gives as best Keplerian solution a period of 10.72 ± 0.007 days and a radial-velocity semi-amplitude $K = 115 \pm 2\,\mathrm{m\,s^{-1}}$, a secure result at the CORALIE precision level (Queloz et al. 1999, 2000), even

[4] The discovery was announced beginning of September 1999

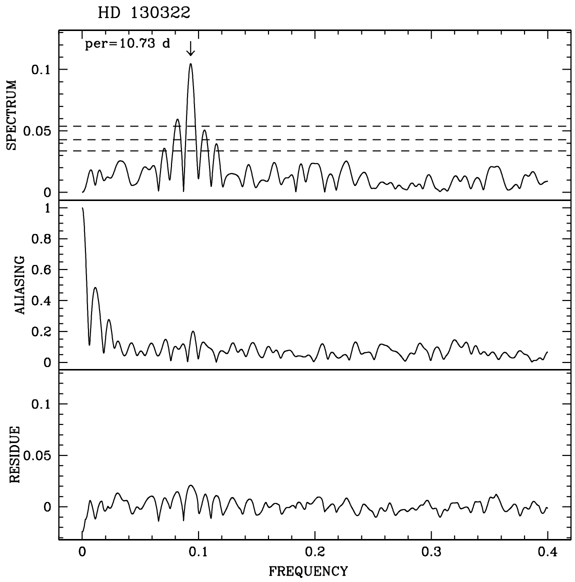

Fig. 4. Fourier power spectrum of the radial-velocity measurements (upper panel) for HD 130322. The middle panel gives the alias spectrum due to the data sampling and the lower panel the residue after removing the contribution of the main peak and its aliases. The radial-velocity period comes out significantly. Horizontal lines represent (from bottom to top) 0.5, 0.05 and 0.001 false-alarm probabilities

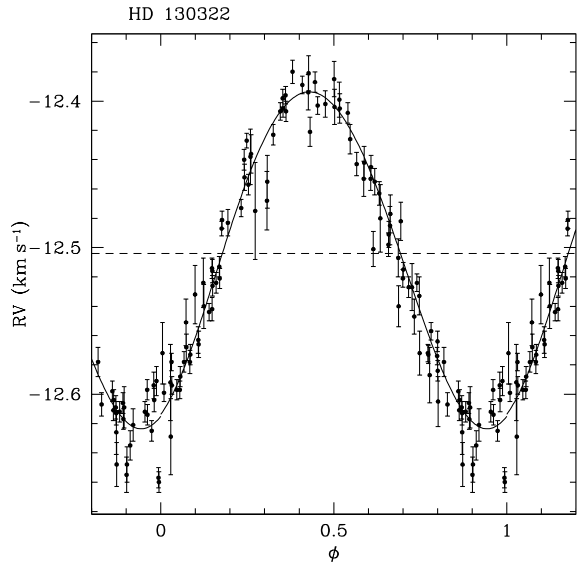

Fig. 5. Phase-folded radial-velocity measurements obtained with CORALIE for HD 130322. Error bars represent photon-noise error

taking into account the somewhat large photon-noise error ($<\varepsilon_i>= 9.2\,\mathrm{m\,s^{-1}}$, peak at $7\,\mathrm{m\,s^{-1}}$) of our actual measurements. With a small but significant eccentricity $e = 0.044 \pm 0.018$, the orbit is almost circular. A temporal Fourier analysis of the radial velocities confirms that uneven data sampling is of no influence on this result (Fig. 4). False-alarm probabilities are also indicated. From the period and mass of the primary star (0.79 $\mathrm{M_\odot}$), the separation between the planet and the star is estimated to be 0.088 AU and the planet minimum mass 1.02 $\mathrm{M_{Jup}}$. Following Guillot et al. (1996), we derive an equilibrium temperature of 720 K at the surface of the planet. The orbital and planetary parameters are given in Table 2 and the phased radial-velocity curve in Fig. 5.

In the same way as for HD 75289, with $v \sin i = 1.9 \pm 1.2\,\mathrm{km\,s^{-1}}$ and taking $R_\star(K0) = 0.85\mathrm{R_\odot}$, the activity index allows us to derive a "calibrated" value for the rotational period $P_{\rm rot}$ = 8.7 days leading to a maximum mass of 6.8 $\mathrm{M_{Jup}}$ for the planet.

According to the 5 CORAVEL measurements taken over more than 11 years, between 1985 and 1996, HD 130322 appears to be a single star.

5. Planetary companions: the best explanation

Most extra-solar giant planets have been detected through the radial-velocity variations of solar-type stars. However, such variations can also be induced by motions of the photosphere due to pulsation (highly unlikely for solar-type stars and several day periods) and/or stellar-activity related variations like star spots or convective inhomogeneities and their temporal evolution over a rotation period. The amplitude of the radial-velocity variations associated with intrinsic phenomena may reach a few tens of $\mathrm{m\,s^{-1}}$ (Saar & Donahue 1997, Saar et al. 1998, Santos et al. 1999b) and can possibly inhibit (when non-coherent) or confuse (on a few rotational periods) planet detections. In case of short-period velocity changes, stellar intrinsic variations have to be ruled out by checking the invariability of the bisector of the spectral lines and the stability of the star luminosity, expected for velocity variations due to orbital motions.

Line bisector measurements require a very high spectral resolution. Such measurements were performed to eliminate activity phenomena and non-radial pulsation for explaining the 51 Peg observations (Gray 1998, Hatzes et al. 1998, Brown et al. 1998a, 1998b). A much easier related diagnostic is directly available from our cross-correlation technique by checking the bisector inverse slope (BIS) of the cross-correlation function (CCF)[5] obtained with a purpose-designed template (Queloz et al. in prep). This technique was very efficiently applied to HD 166435 (Queloz et al. in prep) that was found to be intrinsically variable even though the phase of the radial-velocity variations seemed to be stable for a very long time (several hundreds of cycles). This star presents phased inverse bisector slope and radial-velocity variations of similar amplitudes. The observed in-phase luminosity variation moreover confirms the intrinsic radial-velocity variability for this star.

For our 2 candidates, HD 75289 and HD 130322, the temporal Fourier transforms of the inverse slopes of the CCF bisectors do not show any significant periods (e.g. for HD 75289 there is a 45% chance that the observed maximum peak in the Fourier transform of the bisector data comes from noise and sampling) whereas the radial-velocity periodicities are highly significant (Figs. 2 and 4). Furthermore, in case of phased variations of radial velocities and bisector slopes, we expect a tight correlation

[5] The CCF is seen as an average line of the spectrum

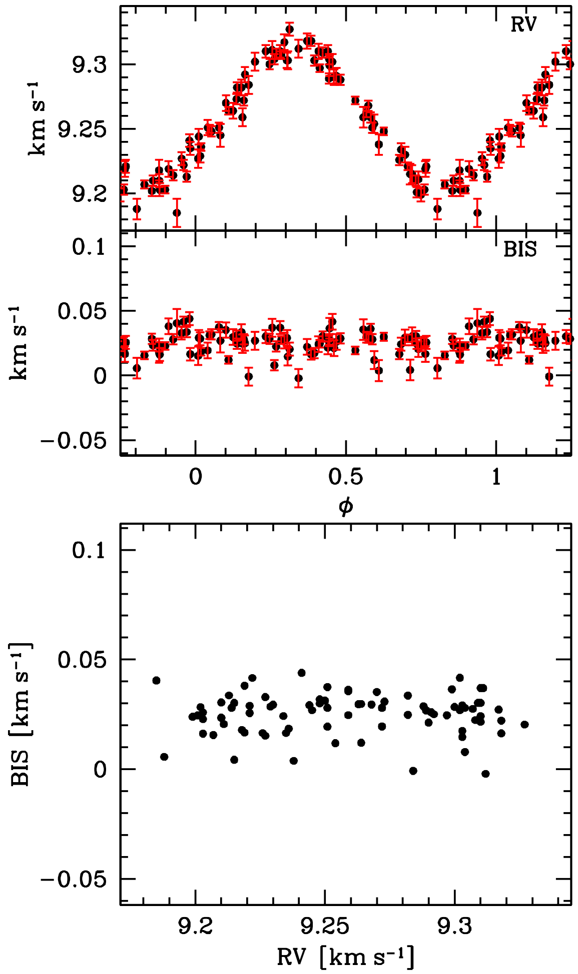

Fig. 6. Top. Radial velocities (RV, upper panel) and inverse bisector slope (BIS, middle panel) phased with the orbital period ($P = 3.51$ d), for HD 75289. **Bottom.** RV vs BIS plot (same scale) showing the independence of the two quantities

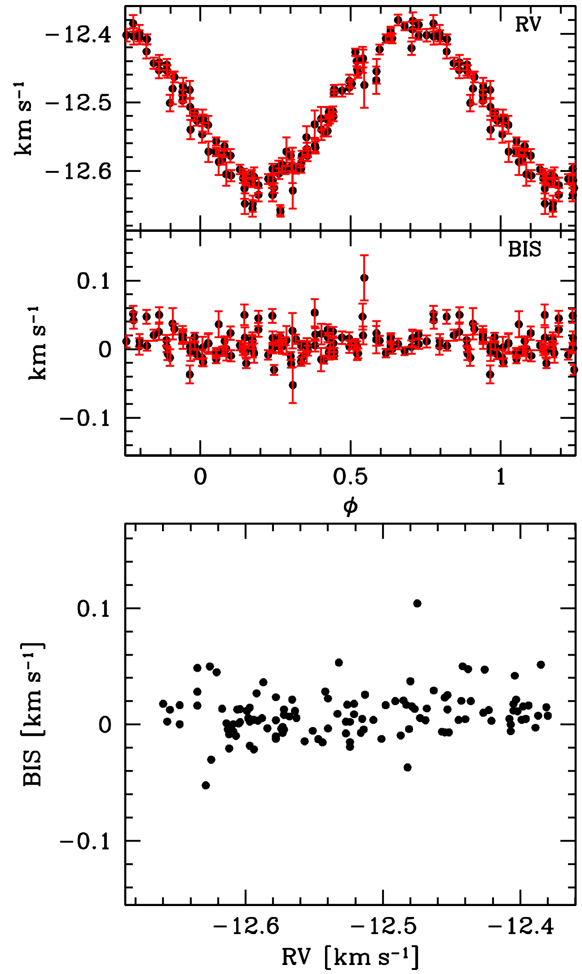

Fig. 7. Same as Fig. 6 for HD 130322 ($P = 10.72$ d)

between these two quantities. This is not observed as shown in the lower diagrams of Figs. 6 and 7 or in the upper panels of those figures that display the radial-velocity (RV) and bisector-slope (BIS) curves phased with the corresponding orbital periods.

This result was expected for HD 75289 whose activity index is very low (Fig. 6, r.m.s. of the BIS measurements = 9 m s^{-1}) and for which the residuals around the Keplerian orbital solution are of the order of individual measurement errors. On the other hand, the fair activity level of HD 130322 and the similitude between the orbital and estimated rotation periods required a posteriori checks to assert the orbital solution for the observations. Even if not coherent, the level of bisector variation is higher for this star (Fig. 7, r.m.s. of the BIS measurements = 20 m s^{-1}) and explains the somewhat large noise (for CORALIE) around the derived best Keplerian solution.

The non-varying luminosity of a star furthermore insures that intrinsic phenomena (e.g. spots) are not acting to produce the observed radial-velocity variations. For HD 75289, the above mentioned transit search insures a high-level short-term photometric stability. For both stars, data taken from HIPPARCOS and from Geneva photometry do not show detectable photometric variations for the given magnitudes. This leaves the planetary interpretation as the only one that explains the observations.

6. Concluding remarks

We have presented two giant-planet candidates, around HD 75289 and HD 130322, detected with the CORALIE echelle spectrograph mounted on the 1.2-m Euler Swiss telescope at La Silla Observatory. Both planets are on quasi-circular orbits close to their parent stars, they have periods of 3.51 and 10.72 days. The inferred minimum masses are 0.42 M_{Jup} (the lightest found to date) and 1.02 M_{Jup}, respectively. These objects were discovered as part of a large radial-velocity monitoring of more than 1650 southern dwarf stars of the solar vicinity, forming a volume-limited sample well-defined for statistical studies as e.g. the distribution of planetary orbital elements or the distribution of (substellar) companions to solar-type stars.

With 4 CORALIE planetary candidates (Gl 86, HD 75289, HD 130322, HD 192263) announced in about 1 year, our observing facility shows its efficiency (precision + observing time availability) for giant-planet detection. Out of our sample we expect to obtain several tens of planet candidates. This will bring stronger statistical constraints for the formation and evolution theories of these systems. The availability of a dedicated telescope is of prime importance for achieving this efficiency. If the stellar variability is rapidly established with the commonly achieved precision, the orbital parameter determination (especially the period and eccentricity) is more affected by the data sampling induced by the observation time windows. This may explain the presently observed lack of systems with semi-amplitude radial-velocity variations smaller than about 35 m s^{-1} which moreover require a large number of measurements and are more sensitive to activity-related noise.

Concerning activity-related noise, it is worth noticing that one of the planetary candidates presented here orbits a fairly active K0 star (HD 130322; $\log(R'_{HK}) = -4.39$). This is also the case for HD 192263 (Santos et al. 2000) which is an active K2 dwarf ($\log(R'_{HK}) = -4.37$). In both cases the radial-velocity jitter induced by activity is small compared to the orbital radial-velocity semi-amplitude and thus did not prevent us from detecting the planet. This illustrates the result pointed out by Saar et al. (1998) and Santos et al. (1999b) that activity-induced radial-velocity noise is becoming smaller when going from late F to K dwarfs. The latters remain thus suitable targets for planet-search programmes even if they show a fair activity level. This is especially true for non- or slowly-rotating stars, knowing that rotation amplifies the spectral line asymmetries induced by the change in the stellar disk illumination due to the presence of stellar spots.

Finally, the combination of bisector analysis and cross-correlation technique (Queloz et al. in prep) provides a robust diagnostic which allows us to confidently rule out intrinsic phenomena for the source of observed radial-velocity variations in the case of short-period planetary companions, as illustrated on our two candidates.

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