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The CORALIE survey for southern extra-solar planets

X. A Hot Jupiter orbiting HD 73256*

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Abstract. Recent radial-velocity measurements obtained with the CORALIE spectrograph on the 1.2-m Euler Swiss telescope at La Silla unveil the presence of a new Jovian-mass Hot Jupiter around HD 73256. The 1.85-$M_{\rm Jup}$ planet moves on an extremely short-period ($P = 2.5486$ d), quasi-circular orbit. The best Keplerian orbital solution is presented together with an unsuccessful photometric planetary-transit search performed with the SAT Danish telescope at La Silla. Over the time span of the observations, the photometric follow-up of the candidate has nevertheless revealed a $P \simeq 14$-d photometric periodicity corresponding to the rotational period of the star. This variation as well as the radial-velocity jitter around the Keplerian solution are shown to be related to the fair activity level known for HD 73256.

Key words. techniques: radial velocities – techniques: photometric – stars: binaries: spectroscopic – stars: individual: HD 73256 – stars: activity – stars: planetary systems

1. Introduction

The increasing timebase of the radial-velocity surveys searching for extra-solar planets allows the different planet-hunter teams to announce new planetary candidates on longer and longer periods. This growing period-interval coverage is very important. With the enlargement of the available statistics, new properties of the planetary period distribution are emerging. They provide interesting new constraints for the migration scenarios (for a recent review see Udry et al. 2003).

On the other hand short-period planets, easier to detect because of the larger reflex motions induced on the primaries and the better phase coverage for orbital-element determinations, were rapidly detected. An almost complete census of these systems is available in well-covered surveys. In the case of our CORALIE planet-search programme (Udry et al. 2000), the number of targets is very large (~1650) and there are still candidates with only few measurements. From this survey, we present here a new short-period planet orbiting the star HD 73256, detected thanks to very recent radial-velocity observations.

The parent star description, radial-velocity measurements, orbital solution and inferred planetary characteristics for this new candidate are presented in Sects. 2 and 3. Hot Jupiters are promising candidates for photometric transit searches so, in Sect. 4, we describe our photometric observations aiming first to detect a potential planetary transit and then to check the star photometric stability. In Sect. 5, we discuss photometric and line bisector measurements in relation to the activity-induced radial-velocity jitter observed on top of the Keplerian orbital variation. Finally, Sect. 6 gives a summary of the results and some concluding remarks.

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* Based on observations collected with the CORALIE echelle spectrograph on the 1.2-m Euler Swiss telescope and the Strömgren Automatic Telescope (SAT) at La Silla Observatory, ESO Chile.

2. Stellar characteristics of HD 73256

HD 73256 (HIP 42214) is a G8/K0 dwarf in the southern *Pyxis* constellation. The HIPPARCOS catalogue (ESA 1997) lists a visual magnitude $V = 8.08$, a colour index $B–V = 0.782$, and a precise astrometric parallax $\pi = 27.38 \pm 0.77$ mas that sets the star at a distance of 36.5 pc from the Sun. Its absolute magnitude is then estimated to be $M_V = 5.27$, slightly overluminous for a typical G8 dwarf. This is probably due to the enhanced metallicity content of the star (see below).

Table 1. Observed and inferred stellar parameters for HD 73256. Definitions and sources of the quoted values are given in the text.

Spectral Type	G8/K0	
V	8.08	
$B-V$	0.782	
π	27.38 ± 0.77	[mas]
M_V	5.27	
L	0.69	[$L_\odot$]
$T_{\rm eff}$	5570 ± 50	[K]
$\log g$	4.66 ± 0.10	[cgs]
[Fe/H]	0.29 ± 0.05	
$M_\star$	1.05	[$M_\odot$]
$R_\star$	0.89	[$R_\odot$]
$v \sin i$	3.22 ± 0.32	[km s^{-1}]
$\log(R'_{\rm HK})$	−4.49	
age($R'_{\rm HK}$)	0.830	[Gyr]
$P_{\rm rot}(R'_{\rm HK})$	13.90	[days]
$P_{\rm rot}$(phot)	13.97	[days]
$v_{\rm eq}$	3.26	[km s^{-1}]

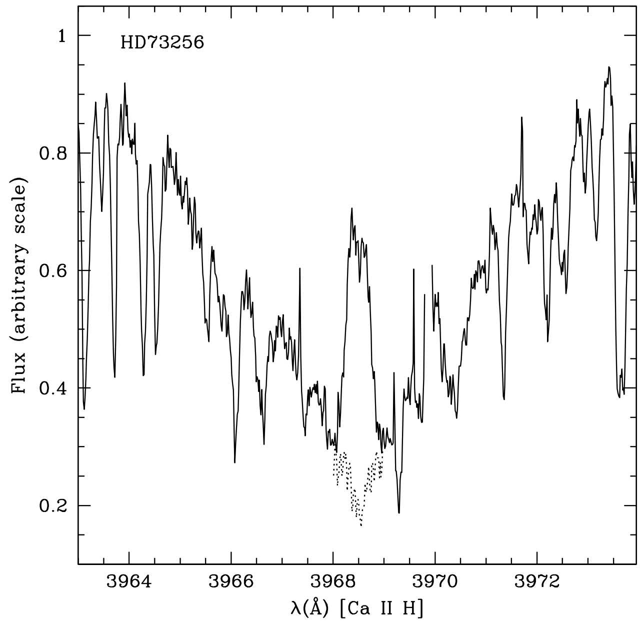

Fig. 1. λ 3968.5 Å Ca II H absorption line region of the summed CORALIE spectra for HD 73256. A clear emission feature is observed. The dotted line in the center of the line represents the spectrum of a non-active star.

From a high-resolution spectroscopic abundance study of HD 73256, we have determined precise values of its effective temperature ($T_{\rm eff} = 5570 \pm 50$ K), metallicity ([Fe/H] $= 0.29 \pm 0.05$) and gravity ($\log g = 4.66 \pm 0.10$), using a standard local thermodynamical equilibrium (LTE) analysis (see Santos et al. 2000c, for error estimates). From calibrations of the width and surface of the CORALIE cross-correlation functions (CCF; described in Santos et al. 2002) we can also derive estimates of $v \sin i = 3.22$ km s^{-1} and [Fe/H] $= 0.27$[1]. The high metal content is a recurrent property of stars hosting planets (for a review see e.g. Santos et al. 2003a, and references therein).

From the colour index and $T_{\rm eff}$ we derive a bolometric correction $BC = -0.122$ (Flower 1996). The star luminosity is then estimated to be $L = 0.69\,L_\odot$. Note however that Flower's calibrations do not take metallicity into account. According to the tracks of the Geneva evolution models with appropriate metal abundance (Schaerer et al. 1993), the position of the star in the HR diagram indicates a mass $M_\star \simeq 1.05\,M_\odot$. This mass is higher than typical values for G8/K0 dwarfs because of the high metallicity of the star.

The models also suggest a completely unconstrained age close to 1 Gyr for the star, in agreement with its measured high activity level. HD 73256 belongs to the sample surveyed by Henry et al. (1996) for Ca II H and K chromospheric emission. It is found to be fairly active with an index $\log R'_{\rm HK} = -4.49$. Chromospheric emission is also directly visible on the coaddition of our CORALIE spectra (Fig. 1). Following the calibration by Donahue (1993), this activity index value points towards a young stellar age around 830 Myr.

From the relation between the activity index and stellar rotation period (Noyes et al. 1984), we derive a period of rotation $P_{\rm rot} \simeq 13.9$ days for HD 73256. Assuming that the orbital and rotation axes coincide[2], a "statistical" equatorial velocity $v_{\rm eq}$ can be derived from the radius of the star. The orbital plane inclination is then obtained from the measured projected rotational velocity $v \sin i = 3.22$ km s^{-1}. Using the simple relation between stellar luminosity, radius and effective temperature $L = 4\pi R^2 \sigma T_{\rm eff}^4$ and with the stellar parameter values given above, the radius is estimated to be $\simeq 0.89\,R_\odot$. This leads to a value $v_{\rm eq} \simeq 3.26$ km s^{-1}, very close to the quoted $v \sin i$ ($\sin i \simeq 0.98$). The true mass of the planet is thus not expected to be very different from the derived minimum mass. The short period and favourable inclination make HD 73256 a good candidate for a photometric transit search (see Sect. 4).

The observed and inferred stellar parameters are summarized in Table 1. Due to the fair activity level of the star some radial-velocity jitter is expected on a typical timescale of the order of the rotational period. This is discussed in Sect. 5.

3. CORALIE orbital solution for HD 73256

The first observation with CORALIE of HD 73256 started in February 2001 (JD = 2 451 964.67). However, almost 2 years elapsed before we observed the star again. Because of the clear radial-velocity difference between the 2 measurements, the star was then intensively followed during more than 2 months. Like this, we have gathered 40 precise radial velocities. The photon-noise errors of individual measurements are typically

[1] These calibrated estimates, although *statistical*, are reliable. A comparison between spectroscopic and CCF-calibrated metallicities yields a small uncertainty of only 0.05 dex due to the calibration (Santos et al. 2002).

[2] This is verified for HD 209458 (Queloz et al. 2000).

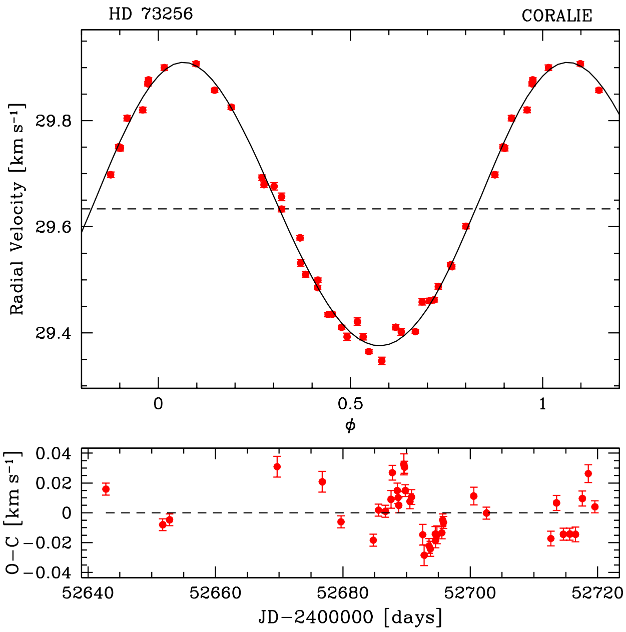

Fig. 2. Phase-folded radial-velocity measurements obtained with CORALIE for HD 73256 (top). Error bars represent photon-noise errors. The still large residuals around the solution (bottom) show some structure and may be explained by activity-induced jitter (see Sect. 5). For clarity of the diagram, the measurement on JD 2 451 964 is not displayed in the figure.

Table 2. CORALIE best Keplerian orbital solution derived for HD 73256 as well as inferred planetary parameters. Uncertainties are estimated through Monte-Carlo simulations.

P	[days]	2.54858	±	0.00016
T	[JD-2 400 000]	52500.18	±	0.28
e		0.029	±	0.02
V	[km s^{-1}]	29.729	±	0.005
ω	[deg]	337.3	±	45.8
K	[m s^{-1}]	269	±	8
$N_{\rm meas}$		40		
σ(O−C)	[m s^{-1}]	14.8		
$a_1 \sin i$	[10^{-5} AU]	6.31	±	0.16
$f(m)$	[10^{-9} $M_\odot$]	5.15	±	0.40
$m_2 \sin i$	[$M_{\rm Jup}$]	1.87	±	0.49
a	[AU]	0.037		
$T_{\rm day\ side}$	[K]	1500		

of 4–5 m s^{-1} despite the relative faintness of the star for our 1.2-m telescope.

The best Keplerian model reproducing the observations yields an accurately constrained orbital period of 2.54858 ± 0.00016 days, a non-significant eccentricity $e = 0.029 \pm 0.02$, and a semi-amplitude $K = 269 \pm 8$ m s^{-1} of radial-velocity variation. Uncertainties are estimated through Monte-Carlo simulations. The phase-folded radial-velocity curve is displayed in Fig. 2 (top).

Using the derived 1.05 $M_\odot$ mass for HD 73256, the best-fit parameters lead to a companion *minimum* mass $m_2 \sin i$ = 1.87 $M_{\rm Jup}$ and a separation $a = 0.037$ AU between the star and the planet. This inferred separation is the 3rd smallest known to date amongst hot Jupiters, after the 2 OGLE (Udalski et al. 2002a,b) candidates recently proposed (Konacki et al. 2003; Dreizler et al. 2003) but for which stronger radial-velocity confirmations are, however, required. At such a small distance the planet is strongly heated by its parent star. From recent models of irradiated planets with condensed dust atmospheres, Barman et al. (in prep.) estimate the planet *day-side* temperature to be around 1500 K (see also Baraffe et al. 2003, for intrinsic temperature estimates). The complete set of orbital elements with their uncertainties and the inferred planetary parameters are given in Table 2.

The measured weighted rms around the solution is σ(O−C) = 14.8 m s^{-1}, a high value compared to the individual photon-noise error. Moreover, some structure is clearly apparent in the residuals drawn as a function of the Julian date (Fig. 2, bottom). The possible periodicity of the residuals is discussed in Sect. 5 in relation with the activity and rotational period of the star.

4. Photometric observations

With its 2.55-day period, the HD 73256 system is a good candidate for photometric transit search. Furthermore, as discussed above, a favourable geometry could be expected from activity indicator and rotational velocity considerations. We have thus rapidly launched an intensive campaign of high-precision differential photometry in order to detect a possible planetary transit.

The photometric *uvby* observations were obtained with the *Strömgren Automatic Telescope* (SAT) at ESO La Silla, Chile. Details on the standard observational and reduction strategy can be found in Clausen et al. (2001). HD 72673, HD 72954AB, and HD 71583 were used as comparison stars. Continuous differential observations were carried out, on two nights, for several hours around the predicted transit times (Fig. 3). Typical rms errors of one magnitude difference are 0.003–0.004 (*ybv*) and 0.005–0.006 (*u*). Unfortunately, no transit indication is found. This implies an orbital inclination smaller than $i \simeq 82.5°$ (i.e. $\sin i \leq 0.99$).

However, the data show different magnitude levels from one night to the other (different symbols in the figure). The star is also known to be active. Thus, in order to check for photometric variability, HD 73256 was also regularly monitored, over several additional nights, to cover the complete interval of orbital phases. The result is shown in Fig. 4 (top) displaying the observed differential magnitudes ($\Delta(y)$) as a function of the Julian date. A periodic variation is clearly visible over the time span of the observations. A Fourier transform of the data[3] yields a period of 13.97 days (Fig. 5), in very good agreement with the rotational period derived from the activity index (13.9 days). The photometric variation can thus be interpreted

[3] Without the last few days for which the photometric phase seems to have changed.

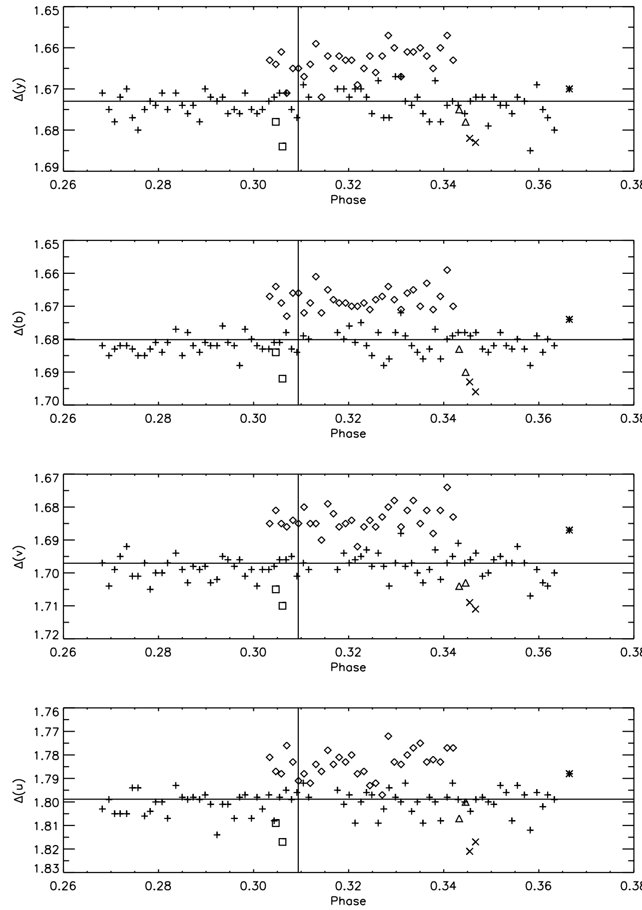

Fig. 3. SAT differential photometric data (HD 73256–HD 72673, instrumental system) around the orbital phase of the potential transit (vertical line), in four different colours of the *Strömgren* photometry, for different nights of observation (different symbols). Typical rms errors of one magnitude difference are 0.003–0.004 (ybv) and 0.005–0.006 (u). The horizontal lines represent the mean magnitude differences (all observations). No indication of a transit is found.

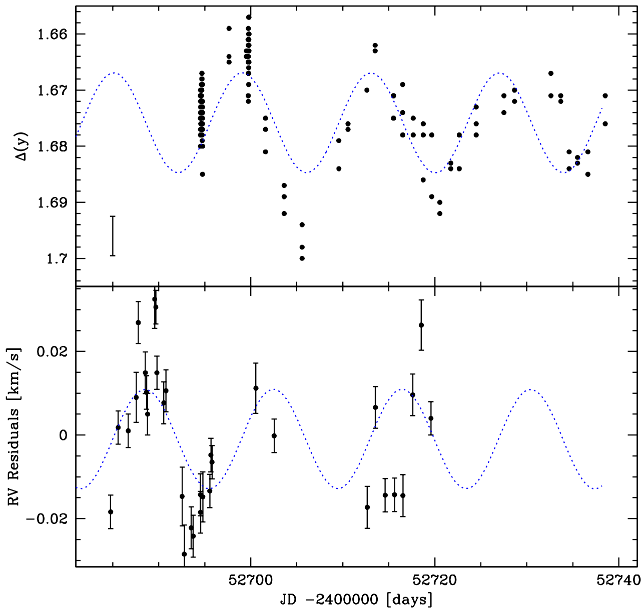

Fig. 4. Top: SAT photometric observations of HD 73256 – HD 72673 in the y band (instrumental system). The typical uncertainty on $\Delta(y)$ is shown in the lower left corner. A periodic structure is clearly appearing in the data. A sine curve with a 13.97-d period (from a Fourier transform) is adjusted to the data and displayed for illustration. **Bottom**: simultaneous radial-velocity residuals around the best Keplerian solution. A sine curve with the *photometric* period is also displayed. The phase shift between the two sine curves is 1.53 rad, close to $\pi/2$, the expected value for spot-induced photometric and radial-velocity variations (Queloz et al. 2001).

as due to spots on the surface of the star. Such spots not only perturb the observed stellar luminosity over a few rotational periods but also induce a spurious radial-velocity jitter, observable as a radial-velocity variation of similar periodicity (see Sect. 5.2 below).

5. Effect of stellar activity

5.1. Ruling out activity as the origin of the main radial-velocity signal

Most extra-solar giant planets have been detected through variations of the observed radial-velocity of solar-type stars. Such variations may also be induced by stellar activity related phenomena (like spots) over a few rotational periods. The corresponding radial-velocity amplitude can reach a few tens of m s^{-1} (Saar & Donahue 1997; Saar et al. 1998; Santos et al. 2000b). Moreover, this amplitude increases with the rotational velocity of the star. For HD 73256, $v \sin i$ is not very high, so we do not expect much effect from activity. Nevertheless, the measured fair activity level of the star calls for an a posteriori check to assert the orbital solution as the best explanation for the observations. First, the photometric measurements vary with a timescale much longer than the orbital period suggesting different origins for the radial-velocity and photometric variations. This can be further checked by controlling the shape of the spectral lines, expected to vary in the case of spot-induced radial-velocity variations. A powerful diagnostic is directly available from our spectra by computing the bisector inverse slope (BIS) of the cross-correlation functions used for the radial-velocity determination (Queloz et al. 2001). In case of phased variations of radial velocities and bisector slopes, we expect a tight correlation between these two quantities. This is not observed for the 2.55-day period phasing of the data (Fig. 6). Also, no indication of variation of the photometric and BIS data is seen in the Fourier space at the position of the orbital period (Fig. 5). We thus can exclude activity as the source of the observed main radial-velocity variation. A planetary companion is the best explanation.

5.2. Activity as the source of radial-velocity noise

We have noticed in previous sections that the star presents periodic patterns in the photometric data and in the residuals around the Keplerian orbital solution as well. We shall now examine the possibility for these variations to be explained by stellar activity-induced spots.

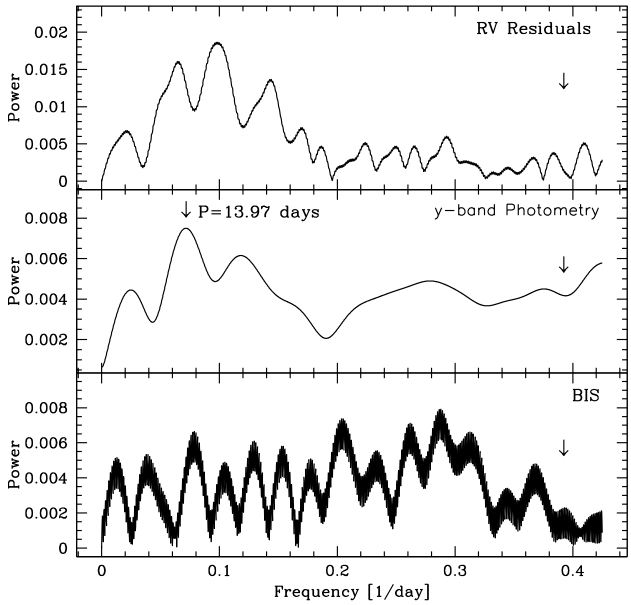

Fig. 5. Fourier transforms of radial-velocity residuals around the Keplerian solution (**top**), SAT photometric $\Delta(y)$ data (**middle**), and CCF-BIS measurements (**bottom**). Photometric and radial-velocity observations share similar behaviours in the frequency space, whereas no coherence is found in the BIS measurements. The rotation period is found at $P_{\rm rot} = 13.97$ days (middle). The vertical arrow on the right hand side in each panel indicates the location of the orbital period.

First, we show that the two quantities present variations of similar timescales (13.97 days), furthermore compatible with the rotation period deduced from the activity index (13.9 days). This is readily visible in Fig. 4 where available simultaneous photometric points and radial velocities (here the residuals around the Keplerian model) are plotted as a function of the Julian date. Fourier transforms of the data also yield similar behaviours in the frequency space (Fig. 5). In Fig. 4, illustrative sine curves with fixed *photometric* period are plotted on top of the points. The phase shift between the two curves (1.53 rad) is close to $\pi/2$, exactly what is predicted for photometric and radial-velocity variations induced by activity-related spots, as shown on HD 166435 by Queloz et al. (2001). Very similar results are obtained in the 4 different bands of the Strömgren photometry.

Another approach consists in comparing the residuals around the orbital solution to the BIS measurements, in the same way as for the actual radial velocities. Figure 7 (top) presents the CCF bisector inverse slope (BIS) measurements and radial-velocity residuals, phased with the rotational period derived from the photometric data. Although the two quantities do not correlate clearly (Fig. 7, bottom), some hints of coupled variations are emphasized in the top panels by the sine curves with fixed 13.97-d period fitted to the data. We are probably reaching here the limit of the method for the available spectral resolution and radial-velocity precision, especially if the BIS signature is much smaller than the radial-velocity jitter in the case of weak rotators, as suggested by Santos et al. (2003b).

The above considerations unambiguously show the link between stellar activity and the radial-velocity spurious noise

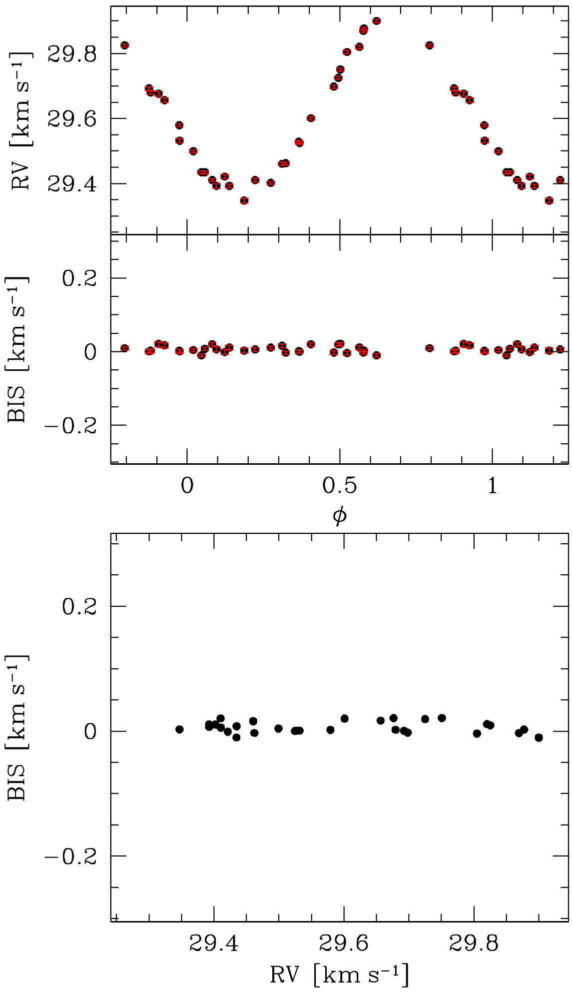

Fig. 6. **Top**: radial velocities (RV, upper panel) and inverse bisector slope (BIS, middle panel) phased with the orbital period (P = 2.5486 d) for HD 73256. **Bottom**: RV vs. BIS plot (same scale) showing the independence of the two quantities.

observed around the orbital solution. Important progresses are expected in the domain with the higher quality spectra and radial velocities to be provided by HARPS (Pepe et al. 2002).

6. Summary and concluding remarks

We have described here a new Hot Jupiter candidate orbiting the star HD 73256, detected with CORALIE as part of our large planet-search survey in the southern hemisphere (Udry et al. 2000). The planet is on a quasi-circular orbit, very close to its parent star. The period is $P = 2.5486$ days. The inferred minimum planetary mass is 1.85 $M_{\rm Jup}$ and the star-planet separation is only 0.037 AU.

A dedicated photometric search for a potential planetary transit has been undertaken as soon as the orbital parameters were known with suitable precision. Although unsuccessful, the photometric measurements allowed us to estimate a stellar rotation period of 13.97 days, much longer than the orbital period. This rules out activity as the source of the observed radial-velocity variation. A further confirmation is brought by CCF bisector measurements showing no correlation with the

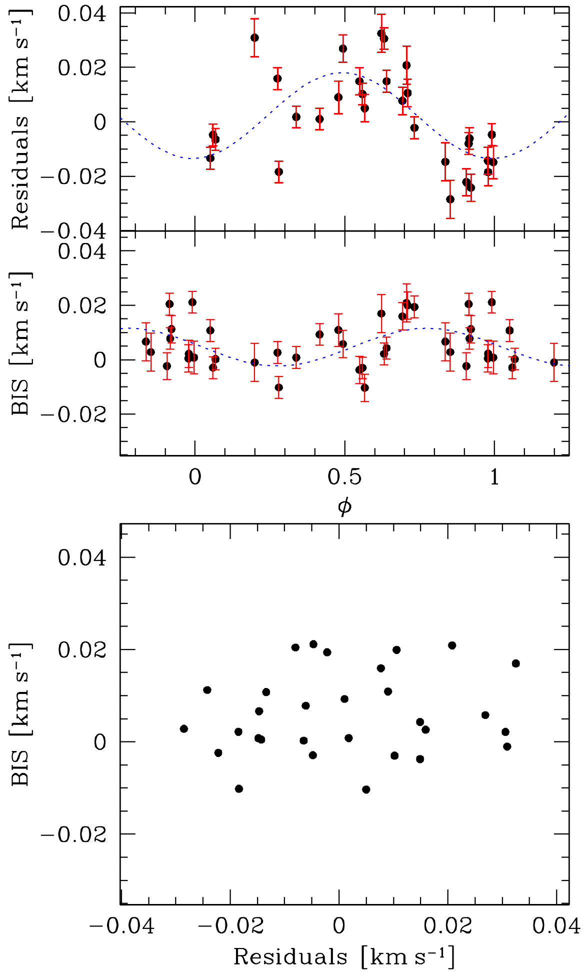

Fig. 7. Same as Fig. 6 but for the residuals around the Keplerian solution, phased with the photometric period ($P = 13.97$ d).

radial velocities. The high activity level of the star is however thought to be responsible for the somewhat large radial-velocity residuals observed around the best Keplerian solution. Comparable variation timescales for the photometric data and residuals support this idea.

Concerning activity-related noise, it is worth noticing that the planet orbits a fairly active late-type dwarf. This is also the case for HD 130322 (Udry et al. 2000) and HD 192263[4] (Santos et al. 2000a, 2003b). In these examples the radial-velocity jitter induced by activity is small compared to the orbital radial-velocity semi-amplitude and thus does not prevent us from detecting the planet. This illustrates the result pointed out by Saar et al. (1998) and Santos et al. (2000b) that activity-induced radial-velocity noise is becoming smaller when going from late F to K dwarfs, a trend mostly due to the typical lower rotation rate of the latters. K dwarfs thus remain suitable targets for planet-search programmes even if they show a significant activity level.

Finally, once again the combination of photometry, CCF bisector analysis and cross-correlation technique (Queloz et al. 2001) has provided the mandatory and robust diagnostics for confidently ruling out activity as the source of the observed radial-velocity variation.

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References

Baraffe, I., Chabrier, G., Barman, T., Allard, F., & Hauschild, H. 2003, A&A, 402, 701
Clausen, J. V., Helt, B. E., & Olsen, E. H. 2001, A&A, 374, 980
Donahue, R. 1993, Ph.D. Thesis, New Mexico State University
Dreizler, S., Hauschildt, P., Kley, W., et al. 2003, A&A, 402, 791
ESA 1997, The HIPPARCOS and TYCHO catalogue, ESA-SP, 1200
Flower, P. 1996, ApJ, 469, 355
Henry, G., Donahue, R., & Baliunas, S. 2002, ApJ, 577, L111
Henry, T., Soderblom, D., Donahue, R., & Baliunas, S. 1996, AJ, 111, 439
Konacki, M., Torres, G., Jha, S., & Sasselov, D. D. 2003, Nature, 421, 507
Noyes, R., Hartmann, L., Baliunas, S., Duncan, D., & Vaughan, A. 1984, ApJ, 279, 763
Pepe, F., Mayor, M., Rupprecht, G., et al. 2002, The Messenger, 110, 9
Queloz, D., Eggenberger, A., Mayor, M., et al. 2000, A&A, 359, L13
Queloz, D., Henry, G. W., Sivan, J. P., et al. 2001, A&A, 379, 279
Saar, S., Butler, R., & Marcy, G. 1998, ApJ, 498, L153
Saar, S., & Donahue, R. 1997, ApJ, 485, 319
Santos, N., Mayor, M., Naef, D., et al. 2000a, A&A, 356, 599
Santos, N., Mayor, M., Naef, D., et al. 2000b, A&A, 361, 265
Santos, N., Israelian, G., & Mayor, M. 2000c, A&A, 363, 228
Santos, N., Mayor, M., Naef, D., et al. 2002, A&A, 392, 215
Santos, N., Israelian, G., Mayor, M., Rebolo, R., & Udry, S. 2003a, A&A, 398, 363
Santos, N., Udry, S., Mayor, M., et al. 2003b, A&A, 406, 373
Schaerer, D., Charbonnel, C., Meynet, G., Maeder, A., & Schaller, G. 1993, A&AS, 102, 339
Udalski, A., Paczynski, B., Zebrun, K., et al. 2002a, Acta Astron., 52, 1
Udalski, A., Zebrun, K., Szymanski, M., et al. 2002b, Acta Astron., 52, 115
Udry, S., Mayor, M., Naef, D., et al. 2000, A&A, 356, 590
Udry, S., Mayor, M., & Santos, N. 2003, A&A, 407, 369

[4] The existence of this planet was recently questioned by photometric measurements showing a periodicity compatible with the orbital period (Henry et al. 2002). New simultaneous photometry and radial velocities show, however, that the two quantities are not correlated (Santos et al. 2003b), contrarily to what is expected in the case of activity (spots) origin for the radial-velocity variations. The planet orbiting HD 192263 is thus back in the list.