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The HARPS search for southern extra-solar planets*

VII. A very hot Jupiter orbiting HD 212301

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ABSTRACT

We report the discovery of a planetary companion orbiting the F8V star HD 212301. This is the first "very hot Jupiter" discovered by a radial velocity survey. The detection was made possible by the HARPS spectrograph installed at the ESO 3.6 m telescope in Cerro La Silla, Chile. The data were carefully analyzed to exclude activity induced effects on the measured radial velocities. Although no transit has been detected, radial velocity oscillations are best explained with a planet of mass $m_2 \sin i = 0.45\ M_{\rm Jupiter}$ orbiting the star at 0.036 AU with a period of 2.246 days.

Key words. stars: individual: HD 212301 – stars: planetary systems – techniques: radial velocities – techniques: spectroscopic – instrumentation: spectrographs

1. Introduction

Since the beginning of the "extra-solar planets era" in 1995 (Mayor & Queloz 1995), more than 160 extra-solar planets have been discovered, a number large enough to allow a flourishing of statistical works on the subject. The great majority of extra-solar planet searches and discoveries are made via the Radial Velocity (RV) method. In this work we used the HARPS[1] spectrograph (Mayor et al. 2003; Pepe et al. 2002; Rupprecht et al. 2004), with a demonstrated RV accuracy of the order of 1 m s^{-1} (Santos et al. 2004b; Lovis et al. 2005), installed at the Cassegrain focus of the ESO 3.6 m telescope at Cerro La Silla (Chile). In addition, we have obtained high-precision differential photometry with the Strömgren Automatic Telescope (SAT) at Cerro La Silla.

We report the discovery of a candidate planet orbiting the star HD 212301 with a period of ≈2.246 days, making it a "very hot Jupiter". Although planets with a shorter period ("hot Neptunes") have been discovered by radial velocity surveys, this is the only "very hot Jupiter" discovered so far via Doppler shift measurements, and it has the fifth shortest orbital period known, the four shorter ones being three OGLE transiting planets: OGLE-TR56, OGLE-TR113, OGLE-TR132 and HD 189733 with orbital periods of 1.2, 1.4, 1.7 and 2.2 days respectively (Bouchy et al. 2004, 2005a,b; Udalski et al. 2003).

"Hot Jupiters" ($M \gtrsim 0.25\, M_{\rm Jupiter}$, $P \leq 10$ days) and "very hot Jupiters" ($M \gtrsim 0.25\, M_{\rm Jupiter}$, $P \leq 2.5$ days) are subject to intense irradiation from their parent star, which affects substantially their structure and evolution. The first measurements of a hot Jupiter atmosphere (HD209458b in the far UV, Vidal-Madjar & Lecavelier des Etangs 2004), point towards escape of the outer atmosphere of the gas giant via dynamical blow-off, tidal forces and classical Jeans escape. (Baraffe et al. 2004, 2005; Lecavelier des Etangs et al. 2004). A similar evolution may be expected for the planet orbiting HD 212301.

* Based on observations made with the HARPS instrument on the ESO 3.6 m telescope under the GTO program ID 072.C-0488 and with the Strömgren Automatic Telescope (SAT) at Cerro La Silla (Chile).
[1] High Accuracy Radial velocity Planet Searcher.

In this paper we present the parent star description in Sect. 2, and the radial-velocity measurements, the orbital solutions and the inferred planetary characteristics for this new candidate in Sect. 3. Section 4 is dedicated to the photometric measurements and Sect. 5 presents the summary and the conclusions of this work.

2. Stellar characteristics of HD 212301

HD 212301 (HIP 42214) is an F8V dwarf in the southern hemisphere. The HIPPARCOS catalog (ESA 1997) lists a visual magnitude $V = 7.76$, a colour index $B - V = 0.56$, and an astrometric parallax $\pi = 18.97 \pm 0.73$ mas that sets the star at a distance of 53 ± 2 pc from the Sun. Its absolute magnitude is then estimated to be $M_V = 4.15 \pm 0.20$.

We have determined precise values of its effective temperature ($T_{\rm eff} = 6256 \pm 28$ K), metallicity ([Fe/H] $= 0.18 \pm 0.04$) and gravity ($\log g = 4.52 \pm 0.05$) from a high-resolution spectroscopic abundance study of HD 212301, using a standard local thermodynamic equilibrium (LTE) analysis (see Santos et al. 2000, for error estimates).

The over-solar metallicity is a recurrent property of stars hosting planets (for a review see e.g. Santos et al. 2001, 2004a, and references therein). The $\log g$ can also be computed as a "trigonometric gravity" (Santos et al. 2004a) using the spectroscopic temperature, the derived mass and the HIPPARCOS parallax, yielding a value of $\log g \approx 4.42 \pm 0.15$, which is not incompatible with the previous estimate. From calibrations of the width and surface of the cross-correlation function (as described in Santos et al. 2002) we can also derive an estimate of $v \sin i$ and of its uncertainty: $v \sin i = 5.44 \pm 1$ km s^{-1}.

The star luminosity is estimated using the effective temperature and the bolometric correction as defined in Flower (1996): $L = 1.75 \pm 0.10\, L_{\odot}$. According to the tracks of the Geneva evolutionary models (Schaerer et al. 1993), the position of the star in the HR diagram indicates a mass $M_{\star} \simeq 1.27 \pm 0.02\, M_{\odot}$.

These models also suggest a completely unconstrained age lower than 1 Gyr, in good agreement with estimates from its $v \sin i$ and the Ca II K line flux (Pace & Pasquini 2004).

The value of the chromospheric flux in the Ca II H and Ca II K lines: $\log R'_{\rm HK} = -4.84 \pm 0.01$, together with the absence of chromospheric re-emission in the core of the Ca II H line (see Fig. 1) and the estimated rotation velocity ($v \sin i = 5.44$ km s^{-1}) indicate that the star is moderately active.

Using Newton's law of gravitation and the inferred $\log g$, we calculate the star radius to be $R = 1.03\, R_{\odot}$. We estimate, from the $\log R'_{\rm HK}$ and the $B - V$ index, a stellar rotation period of $\approx$12 days (Noyes et al. 1984).

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

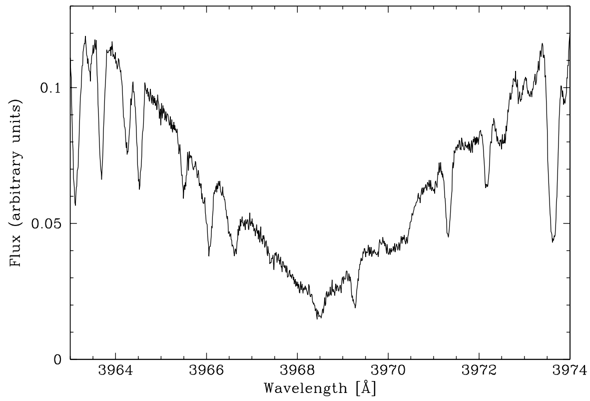

Fig. 1. Ca II H ($\lambda = 3968.47$ Å) absorption line region of the averaged HARPS spectra for HD 212301. Reemission in the core of the line is absent, indicating the level of chromospheric activity of the star is not high.

Table 1. Observed and inferred stellar parameters of HD 212301. Photometric and astrometric parameters are taken from the Hipparcos catalog (ESA 1997). The other stellar physical quantities were obtained from a high-resolution LTE spectral analysis or were interpolated in the grid of Geneva evolutionary models.

Parameter		HD 212301
Sp		F8V
V	[mag]	7.76
$B - V$	[mag]	0.56
π	[mas]	18.97 ± 0.73
M_V	[mag]	4.15 ± 0.20
$T_{\rm eff}$	[K]	6256 ± 28
$\log g$	[cgs]	4.52 ± 0.05
[Fe/H]	[dex]	0.18 ± 0.04
L	[$L_{\odot}$]	1.75 ± 0.10
M_*	[$M_{\odot}$]	1.27 ± 0.02
$v \sin i$	[km s^{-1}]	5.44
$\log R'_{\rm HK}$		−4.84 ± 0.01
$P_{\rm rot}(\log R'_{\rm HK})$	[days]	12
age(model/$\log R'_{\rm HK}$)	[Gyr]	<1

3. A very hot planetary companion for HD 212301

3.1. Observations

The 23 spectra used for the orbital solution were taken in August 2003, June and July 2005.

HD 212301 is not part of the HARPS high precision program (achieving 1 m s^{-1} accuracy, Lovis et al. 2005); the aimed radial velocity accuracy of these observations was of 3 m s^{-1}. Given the very high instrument stability (night drift <1 m s^{-1}) the simultaneous reference method was not used. The target was exposed for a time varying between 1 and 15 min, depending on the atmospheric conditions; the total exposure time for the whole set of measurements was 70 min. The signal to noise obtained at 550 nm varies between 30 and 100, while the error on a single radial velocity measurement varies between 1.2 m s^{-1} and 4.7 m s^{-1}, and includes the photon noise and the calibration errors. The individual radial velocity measurements and the uncertainties are presented in Table 2.

3.2. Orbital solution

The best fit Keplerian model reproducing the data yields an accurately constrained orbital period of 2.245715 ± 0.000028 days, a negligible eccentricity, and a semi-amplitude

Table 2. Individual radial velocities and uncertainties (including calibration errors) for HD 212301. All data are relative to the solar system barycentre.

JD-2400000 [days]	RV [km s^{-1}]	Uncertainty [m s^{-1}]
52 856.82311094	4.6829	1.7
52 857.80050132	4.7449	1.5
52 858.62136607	4.6458	2.7
52 858.88919675	4.6522	3.1
52 859.66580240	4.7497	3.8
52 859.90766115	4.7505	2.0
53 543.83351618	4.6442	1.7
53 544.91732052	4.7377	2.0
53 546.90517819	4.7487	2.4
53 550.83327941	4.6858	3.5
53 551.90755217	4.7019	2.8
53 572.86199991	4.6179	3.0
53 573.82101071	4.7272	3.5
53 574.78693042	4.6441	3.3
53 574.91756610	4.6429	3.6
53 575.72676161	4.7164	3.3
53 575.92553323	4.7473	4.0
53 576.71346667	4.6928	1.4
53 576.86293299	4.6681	1.2
53 577.76521662	4.6849	4.7
53 577.91866426	4.7066	3.5
53 578.82741695	4.7087	1.5
53 579.76714084	4.6457	1.2

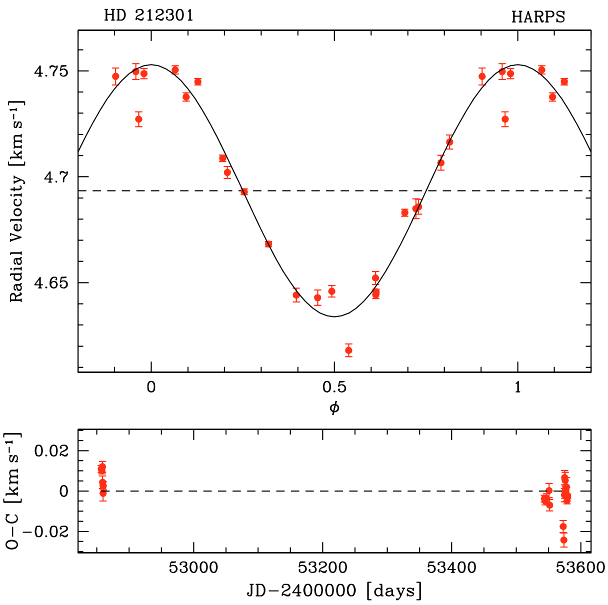

Fig. 2. Phase-folded radial velocities of HD 212301 superimposed to the best Keplerian orbital solution (solid curve). In the lower panel are shown the residuals from the fit against Julian date.

of the radial-velocity variation (K_1) of: 59.5±0.7 m s^{-1}. The uncertainties are estimated from the parameter covariance matrix. The phase-folded radial-velocity curve is displayed in Fig. 2. In Fig. 3 the data points from the two 2005 runs are superimposed to the calculated orbit as a function of Julian date. The residuals are also shown.

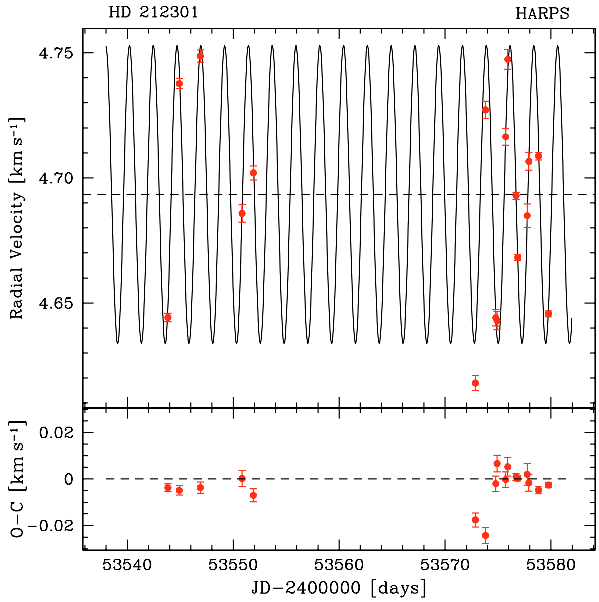

Fig. 3. Radial velocities of HD 212301 as a function of Julian date for the two runs of 2005 superimposed to the best Keplerian orbital solution (solid curve). In the lower panel are shown the residuals from the fit against Julian date.

Table 3. Orbital and physical parameters for HD 212301b.

Parameter		HD 212301b
P	[days]	2.245715 ± 0.000028
T	[JD-2 400 000]	53549.195 ± 0.004
e		0.0 (fixed)
V	[km s^{-1}]	4.6934 ± 0.0005
ω	[deg]	0.0
K_1	[m s^{-1}]	59.5 ± 0.7
$a_1 \sin i$	[10^{-5} AU]	1.229
$f(m)$	[10^{-11} $M_\odot$]	4.913
$m_2 \sin i$	[$M_{\rm Jup}$]	0.45
a	[AU]	0.036
$N_{\rm meas}$		23
Span	[days]	723
σ (O–C)	[m s^{-1}]	6.7

In preliminary fits the fitted eccentricity was zero within the uncertainties. Therefore in the final solution we fixed the eccentricity to zero. The complete set of orbital parameters is shown in Table 3. The measured weighted rms around the solution is σ(O–C) = 6.7 m s^{-1}, a high value compared to the individual photon-noise errors, possibly due to pulsations or to the moderate level of activity of this young star.

In order to be sure that the periodic radial velocity variation originates from a Keplerian orbit we performed several checks.

A bisector analysis was carried out and no correlation was found between changes in radial velocity and variation of the line profile (Spearman correlation is 0.05, also see Fig. 4), a clear indication that the radial velocity oscillation is not due to dark spots moving across the star's surface or other stellar activity (Queloz et al. 2001).

The bisector spans were also plotted against the residuals from the Keplerian fit, as well as against the orbital phase and

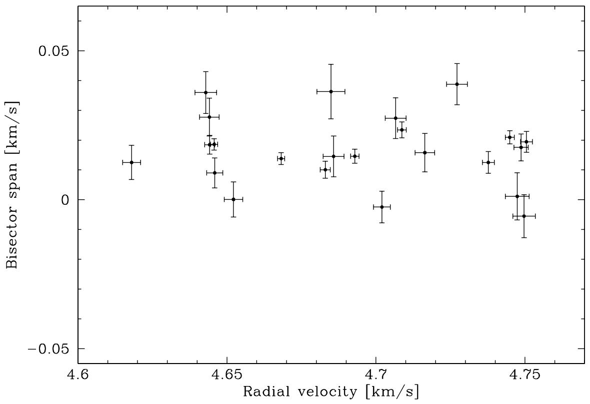

Fig. 4. Bisector velocity span as a function of the measured radial velocity. No correlation is found supporting a non-intrinsic origin for the radial-velocity variation.

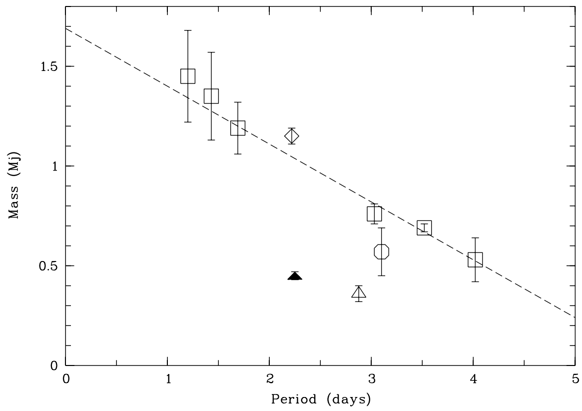

Fig. 5. Mass-period relation for short period transiting planets superimposed to the planet from this work (filled triangle, the minimum mass is plotted). The dashed line is the best linear fit to the earlier transiting planets (open squares) by Mazeh et al. (2005). The open circle corresponds to OGLE-TR 10 (Bouchy et al. 2005a; Konacki et al. 2005), the open triangle to HD 149026b (Sato et al. 2005), and the diamond to HD 189733b (Bouchy et al. 2005b), not included in Mazeh's work.

the star's rotation phase (for a period $P = 12$ days), showing no clear sign of correlation with any of the variables.

The star's rotation period estimate (≈12 days) derived from $\log R'_{\rm HK}$ is different from the orbital period (≈2.246 days). This fact as well suggests that the origin of the measured radial velocity curve is not the stellar activity.

Inspecting the photometric data (Fig. 6) for photometric variation, we notice a slight trend in the data taken with the *b* filter, which however is only marginal when compared to the measurements errors. Therefore we do not expect this minor photometric variation to be related with the main radial velocity oscillation.

We can finally conclude that although, as mentioned in Sect. 2, the star is moderately active and can be responsible for the scatter of the data points around the best-fit orbit and the large residuals (6.7 m s^{-1}), stellar activity or pulsations cannot account for the large amplitude radial velocity periodic oscillation, which is best explained by the star's reflex motion introduced by a low mass orbiting companion.

3.3. Planetary characteristics

Using the derived 1.27 $M_\odot$ mass for HD 212301, the best-fit parameters lead to a companion *minimum* mass $m_2 \sin i = 0.45\,M_{\rm Jup}$ and a separation $a = 0.036$ AU between the star and the planet. The complete set of orbital elements with their uncertainties and the inferred planetary parameters are given in Table 3.

Within the class of hot Jupiters discovered by radial velocity surveys HD 212301b is the closest to its parent star. At such a small distance the planet is strongly heated. Using the prescription by Guillot (Guillot et al. 1996) and assuming efficient redistribution of the heat by the atmosphere and a Jupiter like albedo (0.35), we obtain an equilibrium surface temperature of about 1500 K. Moreover we expect the planet rotation to be tidally locked with its orbit, i.e. the planet always presents the same face to its star (Guillot et al. 1996).

Figure 5 shows the mass-period relation for all short period transiting planets along with the planet of this work (filled triangle). Mazeh et al. (2005) suggest the existance of a linear mass-period relation on the basis of the earlier detections of short period transiting planets data (open squares).

Planets with initial mass below a critical value should evaporate quickly, leaving the lower part of the plot of Fig. 5 under-populated. Only the transiting planets are used for the fit because their real mass (and not the *minimum* mass) is well known. Both the HD 149026b and the HD 212301b points lie well below the line indicated by Mazeh. Although unlikely, a relocation of the HD 212301b point much closer to the Mazeh line cannot be excluded due to the poor accuracy with which $\sin i$ is determined. If the inconsistency of HD 212301b with the linear mass-period relation is confirmed, we would have two counter examples to the relation proposed by Mazeh. Given that most likely all these planets migrated inwards from wider orbits, the mechanism that determines where migration stops might be different for HD 212301b and HD 149026b. Alternatively these planets could lie below the critical survival mass and their atmosphere evaporate quickly.

Indeed a planet in such a close orbit should evolve and loose part, or possibly all, of its atmosphere (Lecavelier des Etangs et al. 2004; Baraffe et al. 2004), as it has already been measured for HD 209458b (Vidal-Madjar & Lecavelier des Etangs 2004). According to Baraffe et al. (2004), a planet like HD 212301b should evaporate its hydrogen rich envelope in less than 5 Gyr, leaving behind a hypothetical "Chthonian" planet (Baraffe et al. 2005).

4. Photometry

With its 2.246-day period, the HD 212301 system is a good candidate for photometric transit search. Furthermore a favorable geometry could be expected from activity indicator and rotational velocity considerations.

The expected probability for a transit detection for the planet's orbital parameters and the star's estimated radius is ≈12%. We have thus launched straightway an intensive

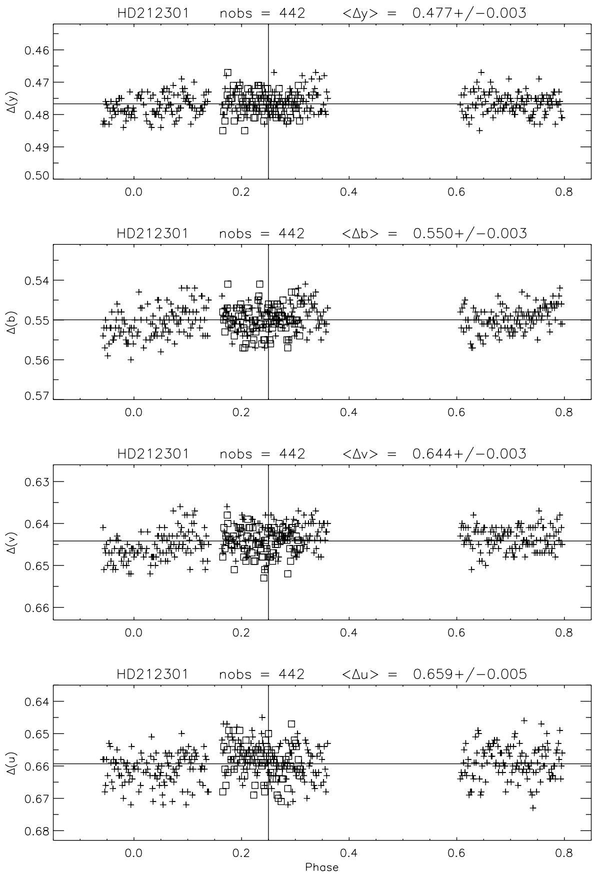

Fig. 6. Differential light curves for HD 212301 showing the 442 observations from all four nights. Symbols are: JD 2 453 585−JD 2 453 589 plus, JD 2 453 594 square. The vertical line indicates the predicted central transit, and the horizontal lines correspond to the mean values of all magnitude differences. Typical rms errors of one magnitude difference are 0.003−0.004 (*ybv*) and 0.005−0.006 (*u*). No indication of a transit is found.

campaign of high-precision differential photometry in order to detect a possible planetary transit.

Photometric *uvby* observations were obtained with the *Strömgren Automatic Telescope* (SAT) at ESO La Silla, Chile and are displayed in Fig. 6. Details on the photometer and the fully automatic mode of the telescope are given by Olsen (Olsen 1993, 1994). Continuous differential observations were carried out on four nights between August 2 and August 12, 2005, and the predicted transit times were covered on two individual nights. Data from both these nights do not show any transit signature nor any correlation with the phase. HD 212748, HD 218827, and HD 219853 were used as comparison stars and were found to be constant within the observational accuracy. Differential magnitudes were formed using for each observation of HD 212301 the two comparison star observations closest in time. All comparison star observations were used with HD 212748 and HD 218827 shifted to the flux level of HD 219853. A total of 442 points were obtained in each band. Typical rms errors of one magnitude difference are 0.003−0.004 (*ybv*) and 0.005 (*u*). Further details on the observational and reduction strategy can be found in the work of Clausen et al. (2001).

From the photometric data we have no indication of a transit (see Fig. 6). This constrains the geometry of the system, allowing only inclination angles smaller than 75 degrees.

In order to check for photometric variability, HD 212301 was monitored over most of the orbital phase interval, including phases outside the predicted transit times.

Only the phase around transit was sampled on more than one night (two nights). A slight trend well away of the transit phase is noticed, in the *b* filter observations; the amplitude of the variation is ≈5 mmag, comparable to the measurements spread. The variation is observed on a single night and in one filter only. There is no clear evidence of a correlation between the RV variation and the photometric one. The origin of the variation is not clear, it could be related to the moderate star's activity, but atmospherics or instrumental effects cannot be excluded.

Therefore we are confident that the measured radial velocity oscillation is not related with this minor flux variation of the star.

5. Summary and concluding remarks

We have described here a new very Hot Jupiter candidate orbiting the star HD 212301, detected with HARPS as part of our large planet-search survey in the southern hemisphere. The planet is in a circular orbit, very close to its parent star. The period is $P = 2.246$ days. The inferred minimum planetary mass is 0.45 $M_{\rm Jup}$ and the star-planet separation is only 0.036 AU.

Activity is shown not to be responsible for the observed radial-velocity variation through bisector line measurements. In particular no correlation is found between the bisector shape and the radial velocities.

A dedicated photometric search for a potential planetary transit has been undertaken as soon as the orbital parameters were known with sufficient precision. Although unsuccessful, the photometric measurements allowed us to show the star's photometric stability at a 0.005 mag level.

The planetary hypothesis is the one which best fits the observed data. Due to the small separation between the planet and its parent star, the equilibrium surface temperature of HD 212301b is ≈1500 K and the planet, now just at the beginning of its evolution history, is expected to evolve and to loose part or all of its atmosphere, possibly ending its lifetime as a "hot Neptune" (hydrogen depleted atmosphere) or a Chthonian planet (no atmosphere).

HD 212301b and HD 149026b appear to deviate from the linear mass-period relation that seemed to be verified for the formerly detected transiting planets with short periods. Although this evidence is not conclusive for HD 212301b, this might suggest different mechanisms at play during the planets formation and migration, or point to a difference in their future evolution.

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This research has made use of the Simbad database, operated at CDS, Strasbourg, France.

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