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Transiting exoplanets from the CoRoT space mission*

XI. CoRoT-10b: a giant planet in a 13.24 day eccentric orbit

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ABSTRACT

Context. The space telescope CoRoT searches for transiting extrasolar planets by continuously monitoring the optical flux of thousands of stars in several fields of view.

Aims. We report the discovery of CoRoT-10b, a giant planet on a highly eccentric orbit ($e = 0.53 \pm 0.04$) revolving in 13.24 days around a faint (V=15.22) metal-rich K1V star.

Methods. We use CoRoT photometry, radial velocity observations taken with the *HARPS* spectrograph, and *UVES* spectra of the parent star to derive the orbital, stellar and planetary parameters.

Results. We derive a radius of the planet of 0.97 ± 0.07 $R_{\rm Jup}$ and a mass of 2.75 ± 0.16 $M_{\rm Jup}$. The bulk density, $\rho_{\rm p} = 3.70 \pm 0.83$ g cm^{-3}, is ~ 2.8 that of Jupiter. The core of CoRoT-10b could contain up to 240 $M_{\oplus}$ of heavy elements.

Moving along its eccentric orbit, the planet experiences a 10.6-fold variation in insolation. Owing to the long circularisation time, $\tau_{\rm circ} > 7$ Gyr, a resonant perturber is not required to excite and maintain the high eccentricity of CoRoT-10b.

Key words. planetary systems – stars: fundamental parameters – techniques: photometric – techniques: spectroscopic – techniques: radial velocities.

1. Introduction

CoRoT is the pioneer space mission dedicated to the detection of extrasolar planets via the transit method (Baglin 2003; see Auvergne et al. 2009 for a detailed description of the instrument and its performance). To date it has led to the discovery of ten extrasolar planets: CoRoT-7b, the first super-Earth with measured radius and mass (Léger et al. 2009; Queloz et al. 2008); three inflated hot Jupiters, CoRoT-1b (Barge et al. 2008), CoRoT-2b (Alonso et al. 2008a) and CoRoT-5b (Rauer et al. 2009); CoRoT-3b, "the first secure inhabitant of the brown dwarf desert" (Deleuil et al. 2008); two Jupiter-like planets with an orbital period of approximately 9 days, CoRoT-4b (Aigrain et al. 2008; Moutou et al. 2008) and CoRoT-6b (Fridlund et al. 2010); the long-period temperate giant planet CoRoT-9b (Deeg et al. 2010), and the hot Super-Neptune CoRoT-8b (Bordé et al. 2010).

Here we report the discovery of the giant planet CoRoT-10b that orbits its parent star in 13.24 days, moving along a highly eccentric orbit with $e = 0.53 \pm 0.04$. It is therefore one of the few known transiting planets with $e \gtrsim 0.5$, such as HD 147056b (alias HAT-P-2b, $e = 0.52$ and orbital period $P = 5.63$ days; Bakos et al. 2007; Pál et al. 2010), HD 17156b ($e = 0.67$ and $P = 21.22$ days; Barbieri et al. 2007, 2009) and HD 80606b ($e = 0.93$ and $P = 111.44$ days ; Moutou et al. 2009; Winn et al. 2009; Hébrard et al. 2010). Eccentric transiting planets include also those with a smaller eccentricity, notably the recently discovered WASP-8b ($e = 0.31$ and $P = 8.16$ days; Queloz et al. 2010) and HAT-P-15b ($e = 0.19$ and $P = 10.9$

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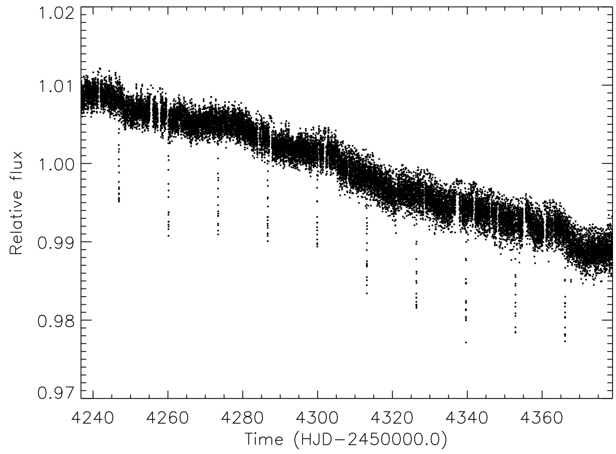

Fig. 1. The quiescent light curve of CoRoT-10 binned at 512 s showing ten transits of the giant planet CoRoT-10b. Jumps due to hot pixels were removed by means of an iterative 3-sigma clipping.

Table 1. CoRoT-10 IDs, coordinates and magnitudes.

CoRoT window ID	LRc01_E2_1802	
CoRoT ID	100725706	
USNO-A2 ID	0900-14919216	
2MASS ID	19241528+0044461	
GSC2.3 ID	NIMR021985	
Coordinates		
RA (J2000)	19:24:15.29	
Dec (J2000)	00:44:46.11	
Magnitudes		
Filter	Mag	Error
B[a]	16.68	0.14
V[a]	15.22	0.05
r'[a]	14.73	0.03
i'[a]	13.74	0.03
J[b]	12.53	0.02
H[b]	11.93	0.03
K[b]	11.78	0.02

[a] Provided by Exo-Dat (Deleuil et al. 2009);
[b] from 2MASS catalogue.

days; Kovács et al. 2010), the massive planet X0-3b (e = 0.26 and P = 3.19 days; Johns-Krull et al. 2008; Winn et al. 2008) and the two Neptunes GJ 436b (e = 0.15 and P = 2.64 days; Gillon et al. 2007a,b; Alonso et al. 2008b; Bean et al. 2008) and HAT-P-11b (e = 0.20 and P = 4.89 days; Bakos et al. 2010).

Transiting planets in eccentric orbits are very intriguing and interesting objects as they allow us to study ongoing tidal dissipation and its impact on the planet radius (Ibgui et al. 2010), atmospheric circulation in the case of a strong variation in insolation (Langton & Laughlin 2007), and the dynamical orbital evolution including the gravitational interaction between planets in a multiple system (planet-planet scattering; e.g., Marzari & Weidenschilling 2002) or the secular influence of a possible distant stellar companion (Kozai mechanism; Kozai 1962).

2. CoRoT observations

The parent star of CoRoT-10b, i.e. the CoRoT target LRc01_E2_1802, is a V = 15.22 star and has been observed in the stellar field pointing towards the constellation of Aquila during the first CoRoT long run LRc01 (Cabrera et al. 2009). Its magnitudes in several photometric bands and its coordinates are reported in Table 1. CoRoT observations of this target lasted for 142.07 days, from the 16$^{\text{th}}$ of May up to the 15$^{\text{th}}$ of October 2007, and provided us with monochromatic (white channel) data (Auvergne et al. 2009).

Transits by CoRoT-10b were first discovered in "alarm mode" (Surace et al. 2008), i.e. while CoRoT observations were still ongoing, which permitted us to change the temporal sampling from 512 s to 32 s after HJD 2454305.11. In total, 210248 photometric measurements were obtained, 198752 in the 32 s oversampling mode [1]. Fig. 1 shows the CoRoT-10 light curve with the nominal sampling of 512 s, filtered from a) outliers that are produced by proton impacts during the crossing of the South Atlantic Anomaly of the Earth's magnetic field by the satellite; and b) several jumps, with a typical duration shorter than 1 day, due to hot pixels . Corrections for the CCD zero offset, sky background, Earth's scattered light and jitter variations were carried out by the latest version 2.1 of the CoRoT reduction pipeline. Unlike CoRoT-2 (Lanza et al. 2009), CoRoT-6 (Fridlund et al. 2010) and CoRoT-7 (Lanza et al. 2010), the light curve of CoRoT-10 is relatively quiescent and does not show flux variations due to the presence of starspots and photospheric faculae greater than a few mmag. It shows a long term decrease of ∼ 2.5% attributable to CCD ageing (Fig. 1). The rms of the nominal and oversampled photometric points is 0.0013 and 0.0046 in relative flux units, respectively.

A total of 10 transits with a depth of ∼ 1.3% are visible in the light curve (Fig. 1). A zoom of one of the five 32 s oversampled transits is shown in Fig. 2. The transit ephemeris, reported in Table 4, was derived from a linear fit to the measured transit mid points determined by a trapezoidal fitting of each transit. It gives an orbital period of 13.2406 ± 0.0002 days.

[1] data available at http://idoc-corot.ias.u-psud.fr/

3. Ground-based follow-up observations

3.1. Radial velocity observations

We performed radial velocity (RV) observations of the star CoRoT-10 with the *HARPS* spectrograph (Pepe et al. 2002b, Mayor et al. 2003) at the 3.6-m ESO telescope (La Silla, Chile). *HARPS* was used with the observing mode obj_AB, without acquisition of a simultaneous Thorium lamp spectrum in order to monitor the Moon background light on the second fibre. The intrinsic stability of this spectrograph does not require the use of lamp calibration spectra, the instrumental drift during one night being in our case always smaller than the stellar RV photon noise uncertainties. *HARPS* data were reduced with the on-line standard pipeline and radial velocities were obtained by a weighted cross-correlation with a numerical spectral mask for a K5V star (Baranne 1996; Pepe et al. 2002a).

The first two measurements of CoRoT-10 were made on June 2008 [2]. Seventeen additional measurements were obtained from June to September 2009[3]. Seven of our nineteen measurements were strongly contaminated by the moonlight: the radial velocity of the Moon was close to that of CoRoT-10 and affected both the RV measurements and the bisector lines. We developed a software correction using the Moon spectrum simultaneously acquired on fibre B: it consists in subtracting the cross-correlation function (CCF) of fibre B, containing the Sun spectrum (reflected by the Moon), from the CCF of the fibre A, containing the stellar spectrum. The correction was applied when the two CCF peaks were close in radial velocity. For CoRoT-10, corrections in the range between 50 and 550 $\mathrm{m\,s^{-1}}$ were applied for seven measurements. To be conservative, we added quadratically 30 $\mathrm{m\,s^{-1}}$ of systematic errors to these seven corrected measurements.

The radial velocities are listed in Table 2 and displayed in Fig. 3 and 4. The phase-folded radial velocity curve shows a variation in phase with the CoRoT transit period. It is compatible with the reflex motion of the parent star due to an eccentric planetary companion. We fitted the data with a Keplerian orbit using the CoRoT ephemeris $P = 13.2406$ days and $T_{tr} = 2454273.3436$ HJD (see Table 4). The derived eccentricity and argument of periastron are $e = 0.53 \pm 0.04$ and $\omega = 218.9 \pm 6.4$ deg. The other orbital parameters are reported in Table 4. The standard deviation of the residuals to the fit $\sigma(O-C) = 29\ \mathrm{m\,s^{-1}}$ is comparable to the mean RV uncertainty.

To examine the possibility that the RV variation is due to a blended binary scenario – a single star with an unresolved and diluted eclipsing binary –, we followed the procedure described in Bouchy et al. (2008) based on checking both the spectral line asymmetries and the dependences of the RV variations on different cross-correlation masks. These two checks excluded that the RV variation is caused by a blended binary and allowed us to establish the planetary nature of CoRoT-10b. The bisector variations are shown in Fig. 5.

2 *HARPS* program 081.C-0388

3 *HARPS* program 083.C-0186

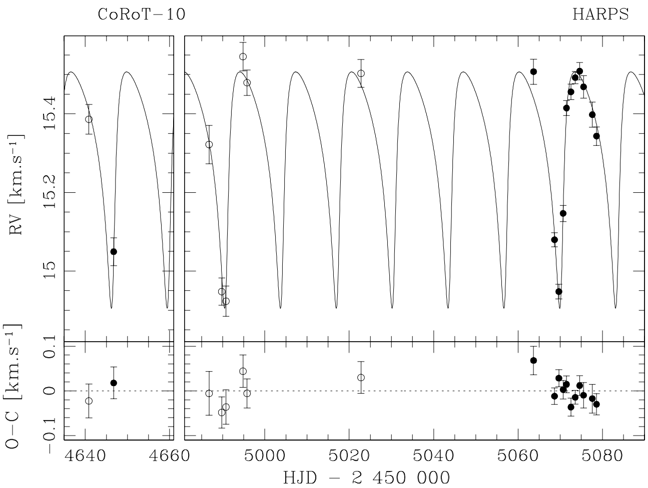

Fig. 3. *Top panel*: radial velocity measurements obtained and the Keplerian best-fit solution (solid line). *Bottom panel*: residuals from the best-fit. The open circles indicate the measurements affected by the moonlight after our correction.

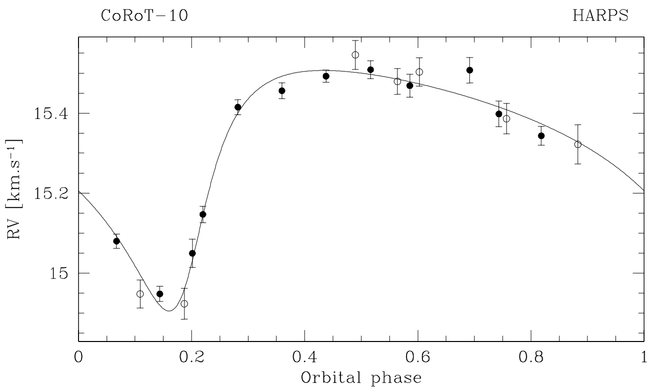

Fig. 4. Phase-folded radial velocity curve of CoRoT-10 and the Keplerian best-fit solution (solid line). The open circles indicate the measurements affected by the moonlight after our correction.

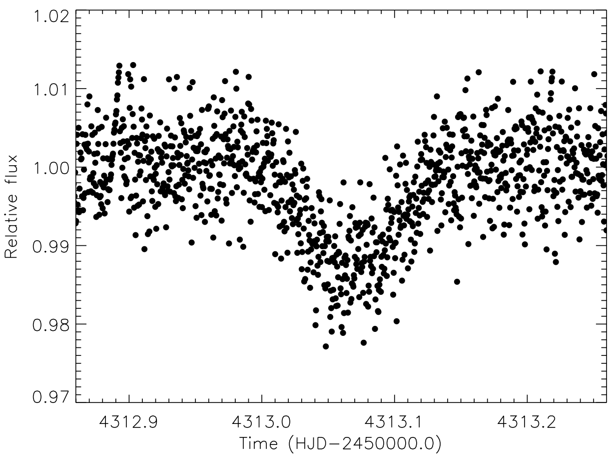

Fig. 2. One of the five 32 s oversampled transits of CoRoT-10b.

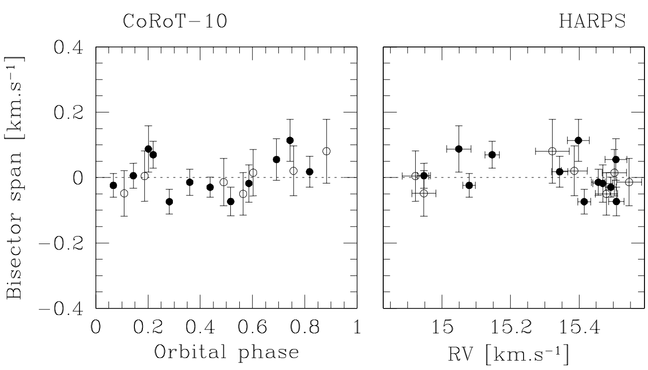

Fig. 5. Bisector variations (span of the bisector slope) as a function of orbital phase (*left pannel*) and radial velocity (*right pannel*). Bisector error bars are estimated as twice the radial velocity uncertainties. No bisector effect is visible for the moonlight-corrected measurements (open circles) indicating the good quality of our correction.

Table 2. Radial velocity measurements of CoRoT-10 obtained by *HARPS*. HJD is the Heliocentric Julian Date. The seven exposures which were affected by the moonlight are labelled with an asterisk and 30 $\mathrm{m\,s^{-1}}$ was quadratically added to their errors.

HJD -2 400 000	RV [$\mathrm{km\,s^{-1}}$]	$\pm1\,\sigma$ [$\mathrm{km\,s^{-1}}$]	BIS [$\mathrm{km\,s^{-1}}$]	exp. time [s]	S/N/pix. (at 550nm)
54640.85815*	15.386	0.038	0.021	3600	7.4
54646.74608	15.049	0.035	0.087	1800	5.1
54986.78569*	15.322	0.049	0.081	3600	4.5
54989.77932*	14.947	0.035	-0.048	3600	9.2
54990.81302*	14.923	0.038	0.004	3600	7.1
54994.81853*	15.545	0.036	-0.014	3600	8.4
54995.80369*	15.479	0.032	-0.050	3600	10.8
55022.79584*	15.503	0.035	0.015	3600	7.0
55063.69761	15.507	0.032	0.055	3300	5.4
55068.67093	15.079	0.018	-0.024	3600	7.7
55069.68356	14.947	0.019	0.006	3300	7.6
55070.69173	15.146	0.021	0.070	3000	7.4
55071.51030	15.414	0.019	-0.074	3000	7.8
55072.54251	15.456	0.020	-0.014	3000	7.5
55073.57439	15.492	0.015	-0.030	3000	9.1
55074.61800	15.508	0.022	-0.073	3600	7.7
55075.53585	15.468	0.029	-0.018	3000	6.4
55077.62048	15.398	0.032	0.114	3000	5.7
55078.61399	15.343	0.024	0.018	3600	7.6

3.2. Photometric observations

Photometric observations during and outside the transit were carried out at the 1.20 m telescope of the Observatoire de Haute Provence during the nights of the 18th of June and the 15th of July 2009, respectively. Such observations are complementary to the radial velocity measurements and are required to definitively exclude the possibility that the transits detected in the CoRoT light curve could be produced by a background eclipsing binary which contaminates the CoRoT aperture mask of the star (Deeg et al. 2009). The latter covers $\sim 16'' \times 14''$ on the sky and contains two main background contaminants: one is 3.78 mag fainter in V and is located at $\sim 6.5''$ from CoRoT-10 toward South-West; the other one is 4.22 mag fainter in V and is $\sim 7.5''$ toward North-East (see Fig. 6). Differential photometry shows an "on-target" transit with the same depth as observed in the CoRoT light curve. None of the two contaminants exhibits significant flux variations that can mimic the transits observed in the CoRoT-10 light curve.

4. Transit fitting

In order to perform the transit fitting, first of all we filtered the raw light curve from outliers due to impacts of cosmic rays. Based on pre-launch observations stored in the Exo-Dat catalogue (Deleuil et al. 2009), we estimated the flux contamination from the two faint background stars which fall inside the CoRoT-10 photometric mask to be 5.5 ± 0.3% (see Fig. 6). We subtracted such a value from the median flux of the light curve (75559 e^-/32 s), which makes the transits slightly deeper by $\sim 7 \cdot 10^{-4}$ in relative flux. We then fitted a parabola to the 5 h intervals of the light curve before the ingress and after the egress of each transit in order to correct for any local variations. We

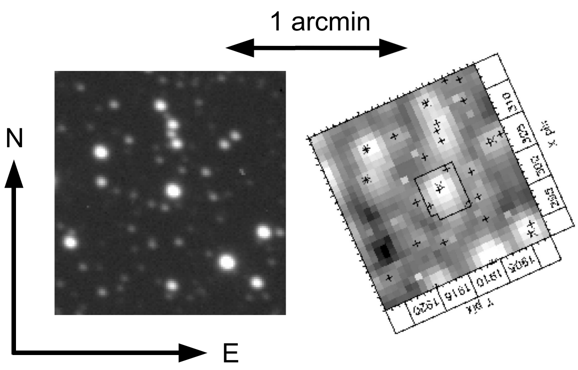

Fig. 6. The sky area around CoRoT-10 (the brightest star near the centre). *Left*: R-filter image with a resolution of $\sim 2.5''$ taken with the OHP 1.20 m telescope. *Right*: image taken by CoRoT, at the same scale and orientation. The jagged outline in its centre is the photometric aperture mask; indicated are also CoRoT's x and y image coordinates and position of nearby stars from the Exo-Dat database (Deleuil et al. 2009).

disregarded two of the ten CoRoT-10b transits, precisely the second transit and the ninth, as their shape was deformed by hot pixels. Finally, we folded the light curve using the ephemeris reported in Table 4 and binning the data points in bins of $8 \cdot 10^{-5}$ in phase, corresponding to ~ 1.5 min (Fig. 7). The error on each bin was computed as the standard error of the data points inside the bin.

Transit best-fit was performed following the formalism of Giménez (2006, 2009) and fixing the eccentricity and the argument of the periastron to the values derived from the Keplerian fit of the radial velocity measurements (see Sect. 3.1). The four free parameters of the transit model are: the transit centre; the phase of the end of transit egress θ_2 in the reference system for eccentric orbits defined by Giménez & Garcia-Pelayo (1983) and shown in their Fig. 1 (see also Giménez 2009); the ratio of the planet to stellar radii $k = R_\mathrm{p}/R_*$, and the inclination i between the orbital plane and the plane of the sky. The two non-linear limb-darkening coefficients $u_+ = u_a + u_b$ and $u_- = u_a - u_b$ [4] were fixed for two reasons: first, the relatively low signal-to-noise ratio of the transit light curve, which does not allow us to constrain either u_+ or u_- within reasonable error bars; secondly, the degeneracy between the inclination and the two limb darkening coefficients in the case of a high impact parameter b, as in our case $b = 0.85 \pm 0.03$ (see Table 4). The adopted limb-darkening coefficients u_a and u_b for the CoRoT bandpass were determined following the procedure in Sing (2010). However, while the latter takes into account only the stellar emergent intensity for the values of $\mu \geq 0.05$, we considered all the 17 values available in the ATLAS model grids [5] down to $\mu = 0.01$. Our choice is motivated by the fact that the transit of CoRoT-

[4] u_a and u_b are the coefficients of the limb-darkening quadratic law: $I(\mu)/I(1) = 1 - u_a(1-\mu) - u_b(1-\mu)^2$, where $I(1)$ is the specific intensity at the centre of the disk and $\mu = \cos\gamma$, γ being the angle between the surface normal and the line of sight

[5] http://kurucz.harvard.edu

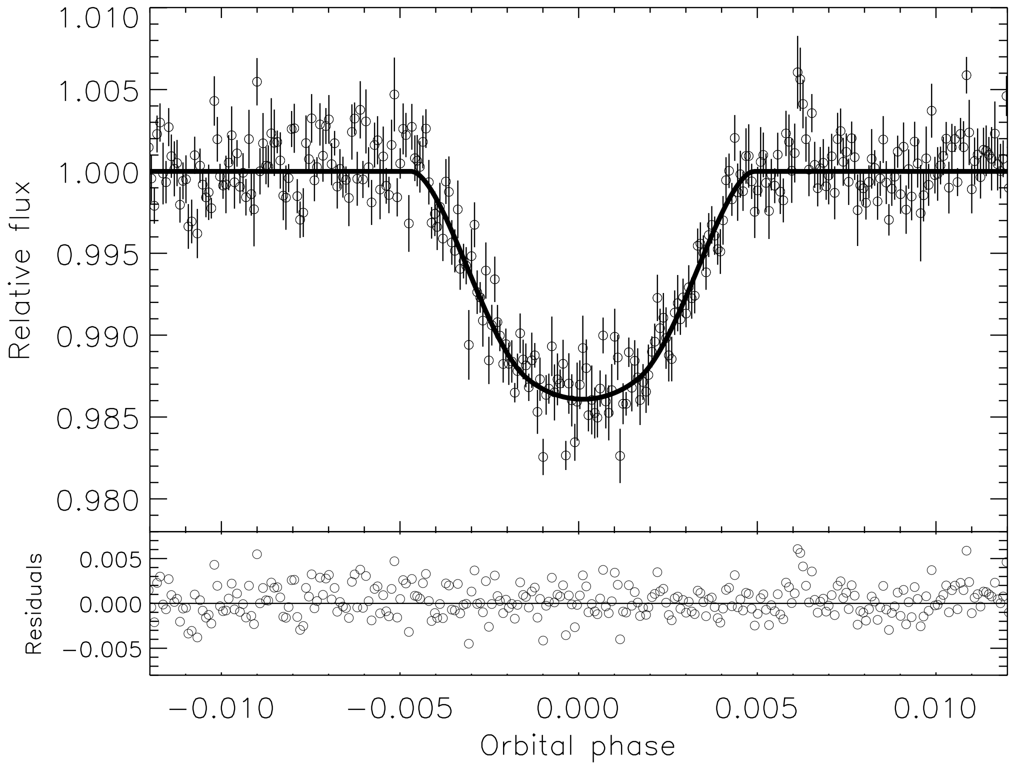

Fig. 7. *Top panel*: Phase-folded light curve of 8 transits of CoRoT-10b. The bin size corresponds to 1.5 min and the 1-sigma error bars on each bin are estimated as the standard error of the data points inside the bin. The solid line shows our best-fit transit model. *Bottom panel*: the residuals from the best-fit model.

10b is grazing, which implies that the variation of the specific intensity close to the limb of the stellar disc must be considered properly when modelling the transit shape. The derived limb-darkening quadratic coefficients are $u_a = 0.51$ and $u_b = 0.21$, which give $u_+ = 0.72$ and $u_- = 0.3$.

The best-fit transit parameters were found by using the algorithm AMOEBA (Press et al. 1992) and changing the initial values of the parameters with a Monte-Carlo method to find the global minimum of the χ^2. Our best-fit of the phase-folded and binned transit light curve is shown in Fig. 7. Fitted and derived transit parameters are listed in Table 4 together with their 1-sigma errors estimated using the bootstrap procedure described in Alonso et al. (2008a) which takes also the correlated noise into account (cf. Alonso et al. 2008a, Sect. 3). Uncertainties on the eccentricity, the argument of the periastron and the contamination were also considered for the estimation of the errors of the derived transit parameters b, a/R_*, a/R_p, $M_*^{1/3}/R_*$ and ρ_*, where b is the impact parameter, a the semi-major axis of the planetary orbit, R_* and M_* the stellar radius and mass, R_p the planet radius, and ρ_* the stellar density (see Table 4). The fitted value of the transit centre is consistent with zero within 1-sigma, which confirms the good quality of the transit ephemeris (Sect. 2).

5. Stellar and planetary parameters

The spectral analysis of the parent star was performed with a high-resolution *UVES* spectrum acquired on the 30th of July 2009[6]. We used the Dic1 mode (390+580) and a slit width of 0.8", achieving a resolving power of ∼55 000. The total exposure time was 4 h leading to a signal-to-noise ratio per pixel S/N∼120 at 5500 Å.

To derive the stellar atmospheric parameters, we first determined the $V \sin i_* = 2 \pm 0.5\,\mathrm{km\,s^{-1}}$. To that purpose, we selected a few *HARPS* spectra that were not contaminated by the Moon reflected light. This series of spectra was set at rest and co-added. To carry out the detailed spectral analysis, we made use of the *VWA* (Bruntt 2009) software package and obtained: $T_\mathrm{eff} = 5075 \pm 75$ K, log g= 4.65 ± 0.10 cm s^{-2} and [Fe/H]= 0.26±0.07 dex. The surface gravity value was checked with usual indicators: Na I D lines around 5890 Å, Mg I b lines, and Ca I lines at 6122, 6162 and 6439 Å. The abundances of several chemical elements are listed in Table 3. The elements for which we could only measure a few lines are not reported.

The absence of noticeable emission in the core of the Ca II H & K lines supports the low magnetic activity of CoRoT-10 indicated by its quiescent light curve (see Fig. 1).

Saturated interstellar Na D lines in the *HARPS* spectra indicate a significant absorption along the line of sight. Converting the 2MASS J and K magnitudes (Table 1) in the Bessel & Brett photometric system (Bessell & Brett 1988), and comparing the $(J-K)$ colour with that expected by Kurucz models for the CoRoT-10 spectral type and metallicity, we found a colour excess $E(J-K) \simeq 0.24$. This corresponds to an extinction of

[6] *UVES* program ID: 083.C-0690(A)

Table 4. Planet and star parameters.

Ephemeris	
Planet orbital period P [days]	13.2406 ± 0.0002
Planetary transit epoch T_{tr} [HJD-2400000]	54273.3436 ± 0.0012
Planetary transit duration d_{tr} [h]	2.98 ± 0.06
Planetary occultation epoch T_{occ} [a] [HJD-2400000]	54276.49 ± 0.41
Planetary occultation duration d_{occ} [h]	2.08 ± 0.18
Epoch of periastron T_0 [HJD-2400000]	54990.85 ± 0.08
Derived parameters from radial velocity observations	
Orbital eccentricity e	0.53 ± 0.04
Argument of periastron ω [deg]	218.9 ± 6.4
Radial velocity semi-amplitude K [$\mathrm{m\,s^{-1}}$]	301 ± 10
Systemic velocity V_r [$\mathrm{km\,s^{-1}}$]	15.330 ± 0.007
O-C residuals [$\mathrm{m\,s^{-1}}$]	29
Fitted and fixed transit parameters	
θ_2 [b]	0.00483 ± 0.00009
Radius ratio $k = R_p/R_*$	0.1269 ± 0.0038
Inclination i [deg]	88.55 ± 0.2
u_+ (fixed)	+0.72
u_- (fixed)	+0.30
Derived transit parameters	
a/R_* [c]	31.33 ± 2.15
a/R_p	247 ± 21
$(M_*/M_\odot)^{1/3}(R_*/R_\odot)^{-1}$	1.33 ± 0.09
Stellar density ρ_* [$g\ cm^{-3}$]	3.32 ± 0.70
Impact parameter b [d]	0.85 ± 0.03
Spectroscopic parameters of the star	
Effective temperature T_{eff}[K]	5075 ± 75
Surface gravity $\log g$ [cgs]	4.65 ± 0.10
Metallicity [Fe/H] [dex]	+0.26 ± 0.07
Stellar rotational velocity $V \sin i_*$ [$\mathrm{km\,s^{-1}}$]	2.0 ± 0.5
Spectral type	K1V
Stellar and planetary physical parameters	
Star mass [$M_\odot$] [e]	0.89 ± 0.05
Star radius [$R_\odot$] [e]	0.79 ± 0.05
Planet mass M_p [$\mathrm{M_{Jup}}$]	2.75 ± 0.16
Planet radius R_p [$\mathrm{R_{Jup}}$]	0.97 ± 0.07
Planet density ρ_p [$g\ cm^{-3}$]	3.70 ± 0.83
Planet surface gravity $\log g_p$ [cgs]	3.93 ± 0.08
Planet rotation period $P_{p,rot}$ [days] [f]	4.25 ± 0.53
Distance of the star d [pc]	345 ± 70
Orbital semi-major axis a [AU]	0.1055 ± 0.0021
Orbital distance at periastron a_{per} [AU]	0.0496 ± 0.0039
Orbital distance at apoastron a_{apo} [AU]	0.1614 ± 0.0047
Equilibrium temperature at the averaged distance T_{eq} [K] [g]	600 ± 23
Equilibrium temperature at periastron T_{eq}^{per} [K] [g]	935 ± 54
Equilibrium temperature at apoastron T_{eq}^{apo} [K] [g]	518 ± 20

[a] $T_{occ} = T_{tr} + \frac{P}{\pi} \cdot \left(\frac{\pi}{2} + (1 + \csc^2 i) \cdot e\ \cos\omega\right)$;

[b] phase of the end of transit egress in the reference system defined by Giménez & Garcia-Pelayo (1983).

[c] $a/R_* = \frac{1+e\cdot\cos\nu_2}{1-e^2} \cdot \frac{1+k}{\sqrt{1-\cos^2(\nu_2+\omega-\frac{\pi}{2})\cdot\sin^2 i}}$, where ν_2 is the true anomaly measured from the periastron passage at the end of transit egress (see Giménez 2009);

[d] $b = \frac{a\cdot\cos i}{R_*} \cdot \frac{1-e^2}{1+e\cdot\sin\omega}$;

[e] from CESAM stellar evolution models. See Sect.5 for details;

[f] assuming the planet to be in a pseudo-synchronous rotation;

[g] black body equilibrium temperature for an isotropic planetary emission.

Table 3. Abundances of some chemical elements for the fitted lines in the *UVES* spectrum. The abundances refer to the solar value and the last column reports the number of lines used.

Element	Abundance	No. lines
Ca I	0.21 ± 0.12	5
Ti I	0.38 ± 0.11	15
V I	0.63 ± 0.12	10
Cr I	0.34 ± 0.13	7
Fe I	0.26 ± 0.10	77
Fe II	0.26 ± 0.11	5
Co I	0.41 ± 0.10	7
Ni I	0.35 ± 0.10	23
Si I	0.37 ± 0.10	8

$A_V \simeq 1.39$ mag[7], in agreement with reddening maps (Schlegel et al. 1998). Using the Pogson formula[8], the stellar distance was estimated to 345 ± 70 pc.

From the transit best-fit we derived a stellar density of $\rho_* = 3.32 \pm 0.70$ g cm^{-3}, i.e. $2.35 \pm 0.50\ \rho_\odot$. CESAM (Morel 2008) and STAREVOL (Palacios, private communication; Siess 2006) models of stellar evolution do not foresee any evolutionary track that matches the above-mentioned stellar density, given the effective temperature and the metallicity of CoRoT-10. Specifically, they predict an upper-limit of 2.55 g cm^{-3} (1.79 $\rho_\odot$), compatible at 1.1-sigma with the stellar density derived from the transit fitting. The mass and radius of the star provided by the CESAM evolutionary tracks are respectively equal to $M_* = 0.89 \pm 0.05$ M$_\odot$ and $R_* = 0.79 \pm 0.05$ R$_\odot$. The corresponding surface gravity, $\log g = 4.59 \pm 0.06$ cm s^{-2}, is in good agreement with the spectroscopic value. The stellar age constraints are relatively weak but favor values smaller than 3 Gyr.

From the aforementioned stellar radius and mass, we determined the radius of the planet $R_{\rm p} = 0.97 \pm 0.07$ R$_{\rm Jup}$ and its mass $M_{\rm p} = 2.75 \pm 0.16$ M$_{\rm Jup}$. The bulk density, $\rho_{\rm p} = 3.70 \pm 0.83$ g cm^{-3}, is ~ 2.8 that of Jupiter.

6. Discussion and conclusions

We report the discovery of CoRoT-10b, a transiting planet on a highly eccentric orbit ($e = 0.53 \pm 0.04$) with a mass of 2.75 ± 0.16 M$_{\rm Jup}$ and a radius of 0.97 ± 0.07 R$_{\rm Jup}$. It orbits a metal rich ([Fe/H] = 0.26 ± 0.07) K1V star with a visual magnitude $V = 15.22$ in 13.24 days. Fig. 8 shows the position of CoRoT-10b in the eccentricity-period diagram of the known extrasolar planets and highlights its peculiarity as it belongs to the class of the few transiting exoplanets with highly eccentric orbits ($e \gtrsim 0.5$) among which HAT-P-2b, HD 17156b and HD 80606b.

To investigate the internal structure of CoRoT-10b, we computed planetary evolution models with CEPAM (Guillot & Morel 1995) under the standard hypothesis that the planet is made up of a central rocky core of variable mass and of an overlying envelope of solar composition (e.g., Guillot 2008). The results in terms of planetary size as a function of system age are shown in Fig. 9. The coloured regions (red, blue, yellow-green) indicate the constraints derived from the stellar evolution models at 1, 2 and 3 σ level, respectively. Assuming a zero Bond albedo, we derived the equilibrium temperature of the planet $T_{\rm eq} = 600$ K. For this temperature, models of planet internal structure with a core mass of 0, 20, 60, 120, 180, 240 and 320 M$_\oplus$ were computed (Fig. 9). Note that a 25% change in the equilibrium temperature yields a difference in the resulting planetary radius of less than 1%. Therefore, a Bond albedo considerably different from zero (up to $A_{\rm B} = 0.7$) does not change significantly our results.

CoRoT-10b is a high density planet with a mass and density similar to those of HD 17156b (Barbieri et al. 2009) but with a higher content of heavy elements. For an age of the star and hence of the planetary system between 1 and 3 Gyr, CoRoT-10b should contain between 120 and 240 M$_\oplus$ of rocks in its interior (i.e. between 14 and 28% of the total mass), at 1-sigma level. Mixing heavy elements in the envelope rather than assuming that they are all contained in the core may yield a reduction of these numbers by ~ 30% (Baraffe et al. 2008). This number is uncertain however because it does not account for the increase in opacity in the outer radiative zone that would have the opposite effect (Guillot 2005). In any case, CoRoT-10b is found to be extremely enriched in heavy elements, suggesting that its formation probably required giant collisions (see Ikoma et al. 2006). It also strengthens the observed correlation between star metallicity and heavy elements in the planet (Guillot 2008).

Moving along its eccentric orbit from the periastron to the apoastron, CoRoT-10b experiences a 10.6-fold variation in insolation. Moreover, since the tidal interaction with the parent star is strongest around periastron, the planet is expected to be in pseudo-synchronous rotation. Eq. 42 from Hut (1981) gives a rotation period of the planet $P_{\rm p,rot} = 4.25 \pm 0.53$ days. Time-dependent radiative models of planetary atmospheres could be

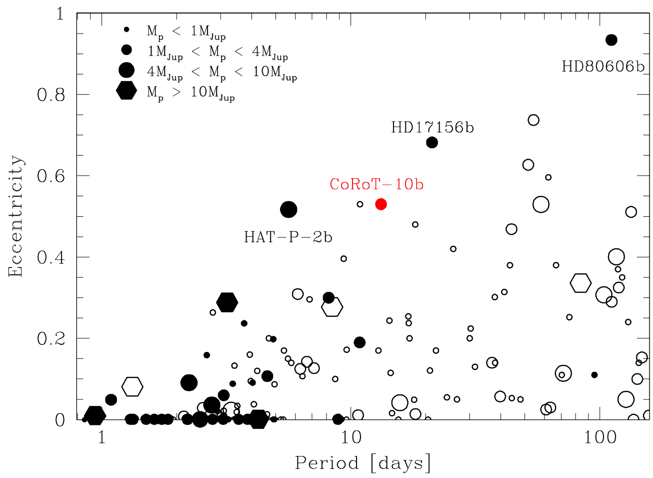

Fig. 8. Eccentricity - period diagram for the known extrasolar planets (black filled symbols are transiting planets). The size of the symbol indicates the mass range. CoRoT-10b, with $P = 13.24$ days and $e = 0.53$, is indicated by the red filled circle. Data from http://exoplanet.eu.

[7] $A_V/E(J-K) = 5.82 \pm 0.1$ (Cox 2000)

[8] $V - M_V = 5 \log d - 5 + A_V$, where M_V was determined from the bolometric magnitude, given the $T_{\rm eff}$ and R_* of CoRoT-10, and the BC taken from http://kurucz.harvard.edu for the atmospheric parameters of CoRoT-10

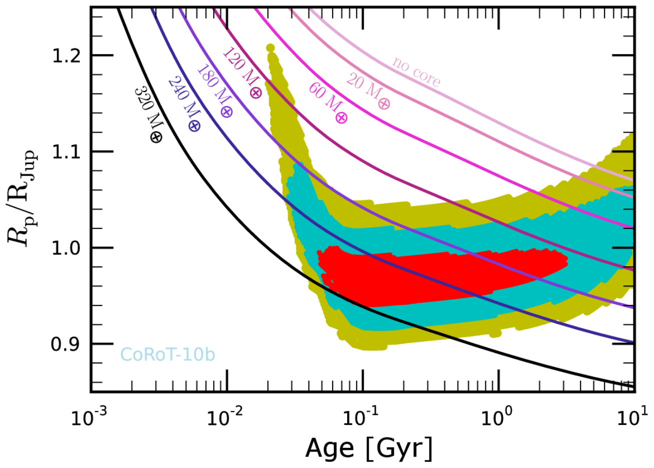

Fig. 9. Evolution of the radius of CoRoT-10b (in Jupiter units) as a function of age, compared to constraints inferred from CoRoT photometry, spectroscopy, radial velocimetry and CESAM stellar evolution models. Red, blue and green areas correspond to the planetary radii and ages that result from stellar evolution models matching the inferred $\rho_* - T_{\rm eff}$ uncertainty ellipse within 1σ, 2σ and 3σ, respectively. Planetary evolution models for a planet with a solar-composition envelope over a central dense core of pure rocks of variable mass are shown as solid lines. These models assume a total mass of 2.75 $M_{\rm Jup}$ and an equilibrium temperature of 600 K (corresponding to a zero Bond albedo). They depend weakly on the assumed opacities, and uncertainties due to the atmospheric temperature and planetary mass are negligible.

used to study heating variations due to the changing star-planet distance at different pressure levels of the planet atmosphere and to predict temperature inversions caused by strong heating around periastron, as done by Iro & Deming (2010) for HD 17156b and HD 80606b.

Using Eq. 6 in Matsumura et al. (2008), we can estimate the circularisation time $\tau_{\rm circ}$ of the planetary orbit, neglecting the stellar damping. The circularisation time strongly depends on the adopted tidal quality factor for the planet $Q'_{\rm p}$ which is not well known. For Jupiter, $5 \cdot 10^4 < Q'_{\rm p} < 2 \cdot 10^6$ (Yoder & Peale 1981; Lainey et al. 2009) and for most of the giant extrasolar planets $10^5 < Q'_{\rm p} < 10^9$ (see Fig. 2 from Matsumura et al. 2008). Considering $Q'_{\rm p} = 10^5$, we find $\tau_{\rm circ} \sim 7.4$ Gyr. Owing to the long circularisation time, the eccentricity of CoRoT-10b need not be excited and maintained by the resonant interaction with another planet. Nevertheless, the eccentric orbits of extrasolar planets can be explained by gravitational planet-planet scattering (e.g., Chatterjee et al. 2008 and references therein). If another massive planet survived the violent encounters between planets and is currently orbiting around the parent star, it could be detected by a long-term radial velocity follow-up of the parent star, e.g., showing a long-term drift induced by the distant companion. If the star has a distant companion of stellar nature, the high eccentricity of CoRoT-10b could be produced by Kozai oscillations rather than planet-planet scattering (e.g., Takeda & Rasio 2005). Distinguishing between the two scenarios would make us understand the dynamical evolution of the eccentric giant planet CoRoT-10b.

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