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Transiting exoplanets from the CoRoT space mission⋆

XII. CoRoT-12b: a short-period low-density planet transiting a solar analog star

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ABSTRACT

We report the discovery by the CoRoT satellite of a new transiting giant planet in a 2.83 days orbit about a $V = 15.5$ solar analog star ($M_* = 1.08 \pm 0.08\ M_\odot$, $R_* = 1.1 \pm 0.1\ R_\odot$, $T_{\rm eff} = 5675 \pm 80$ K). This new planet, CoRoT-12b, has a mass of $0.92 \pm 0.07\ M_{\rm Jup}$ and a radius of $1.44 \pm 0.13\ R_{\rm Jup}$. Its low density can be explained by standard models for irradiated planets.

Key words. planetary systems – star: individual: CoRoT-12 – techniques: photometric – techniques: radial velocities – techniques: spectroscopic

1. Introduction

Because of their special geometric configuration, a wealth of information can be learned about transiting extrasolar planets (e.g., Winn 2010), making them very important for our understanding of the vast planetary population hosted by our galaxy. They are the only exoplanets for which accurate measurements of the mass and radius are available. Furthermore, their atmospheric properties can be studied during their transits and occultations (e.g., Deming & Seager 2009).

More than 70 extrasolar planets transiting their parent stars are now known[1], most of which having been discovered by dedicated photometric surveys. Among these, the CoRoT (Convection, ROtation, and planetary Transits) space mission (Baglin et al. 2009) stands out as a pionner project. Because of its excellent instrumental capabilities and its low Earth orbit, CoRoT can monitor the same fields of view with a very high photometric precision for up to five months. This makes possible the detection of planets that would be out of reach for ground-based surveys, as demonstrated for instance by its discovery of the first transiting "Super-Earth" CoRoT-7b (Léger et al. 2009; Queloz et al. 2009), and the first "temperate" transiting gaseous planet CoRoT-9b (Deeg et al. 2010).

We report here the discovery of a new planet by CoRoT, a "hot Jupiter" called CoRoT-12b that transits a $m_V = 15.5$ solar analog star. We present the CoRoT discovery photometry in Sect. 2. The follow-up, ground-based observations establishing the planetary nature of CoRoT-12b are presented in Sect. 3, while the spectroscopic determination of the parameters of the host star is described in Sect. 4. A global Bayesian analysis of the CoRoT and follow-up data is presented with its results in Sect. 5. Finally, we discuss the inferred properties of the CoRoT-12 system in Sect. 6.

⋆ The CoRoT space mission, launched on December 27, 2006, has been developed and is operated by CNES, with the contribution of Austria, Belgium, Brazil, ESA (RSSD and Science Program), Germany and Spain.

[1] See, e.g., Jean Schneider's Extrasolar Planet Encyclopedia at http://exoplanet.eu

2. CoRoT photometric observations

Table 1 presents the ID, coordinates and magnitude of CoRoT-12. This star is located in a field near the galactic anticenter direction, in the *Monoceros* constellation. It was monitored by CoRoT from October 24, 2007 to March 3, 2008 (CoRoT run *LRa*01; see Rauer et al. 2009; Carone et al. in prep.).

The transits of CoRoT-12b were noticed after 29 days by the so-called "alarm mode" pipeline (Surace et al. 2008). The time-sampling was then changed from 512 s, the nominal value, to 32 s. The processed light curve (LC) of CoRoT-12 is shown in Fig. 1. This monochromatic LC consists of 258 043 photometric measurements for a total duration of 131 days. It results from the processing of the raw CoRoT measurements by the standard CoRoT pipeline (version 2.1, see Auvergne et al. 2009), followed by a further processing (outliers rejection and systematics correction) similar to what is described by, e.g., Barge et al. (2008) and Alonso et al. (2008). 47 transits of CoRoT-12b are present in the LC, 36 of them being found in its oversampled part. Some discontinuities are present in the LC. They were caused by energetic particles hits during the crossings of the South-Atlantic Anomaly by the satellite. A large jump of the measured flux (more than 5%) caused by the impact of a cosmic ray on the detector can also be noticed in the last part of the LC.

Table 1. IDs, coordinates and magnitudes for the star CoRoT-12.

CoRoT window ID	LRa01 E2 3459	
CoRoT ID	0102671819	
UCAC2 ID	31290403	
USNO-A2 ID	0825-03015398	
USNO-B1 ID	0887-0101512	
2MASS ID	J06430476-0117471	
GSC2.3 ID	SB3BK006251	
Coordinates		
RA (J2000)	06 43 03.76	
Dec (J2000)	−01 17 47.12	
Magnitudes		
Filter	Mag	Error
B^a	16.343	0.080
V^a	15.515	0.052
r'^a	15.211	0.040
i'^a	14.685	0.069
J^b	14.024	0.029
H^b	13.630	0.030
K^b	13.557	0.041

Notes. [(a)] Provided by Exo-Dat (Deleuil et al. 2009); [(b)] from 2MASS catalog (Skrustkie et al. 2006).

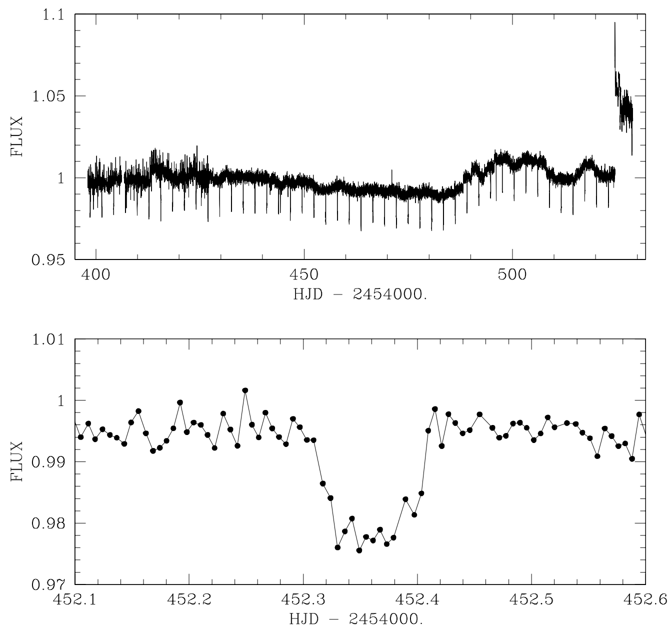

Fig. 1. *Top*: normalized CoRoT LC of the star CoRoT-12. The oversampled part of the LC was binned to the same time bin than its first part for the sake of clarity. *Bottom*: zoom on a transit of CoRoT-12b.

The processed LC shown in Fig. 1 has an excellent duty cycle of 91%.

Despite that its CoRoT LC shows some kind of irregular variations with a peak-to-peak amplitude of 2.3%, CoRoT-12 appears to be a photometrically quiet star. Except for the transit signal (see below), the discrete Fourier-transform of the LC shows no clear periodicity over the noise level. The rotational period of the star cannot thus be constrained from the CoRoT photometry.

Periodic transit-like signals are clearly visible in the LC, as can be seen in Fig. 1. Initial values for the orbital period P and transit epoch T_0 were determined by trapezoidal fitting of the transit centers, as described by Alonso et al. (2008). The resulting values were $T_0 = 2\,545\,398.6305 \pm 0.0002$ HJD and $P = 2.82805 \pm 0.00005$ days. These values were used to schedule the ground-based follow-up observations (see next section), and also as initial guesses for the global analysis presented in Sect. 5.

3. Ground-based observations

The following ground-based observations were performed to establish the planetary nature of CoRoT-12b and to better characterize the system.

3.1. Imaging – contamination

CoRoT has a rather poor optical resolution, so performing high-resolution ground-based imaging of its fields is important, not only to assess the possibility that the eclipse signals detected by CoRoT are due to contaminating eclipsing binaries, but also to estimate the dilution of the eclipses measured by CoRoT caused by contaminating stars (see Deeg et al. 2009, for details).

Imaging of the target field was undertaken with the 2.5 m INT telescope during pre-launch preparations (Deleuil et al. 2009) and with the IAC80 telescope during candidate follow-up (Deeg et al. 2009). It found no nearby contaminating star that could be a potential false alarm source, i.e. that mimiks CoRoT's signal while being an eclipsing binary star (see Fig. 2).

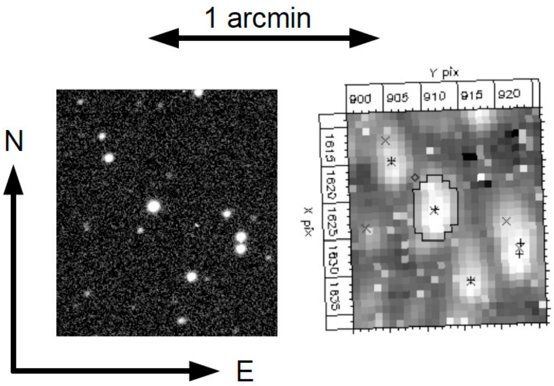

Fig. 2. The sky area around CoRoT-12 (brightest star near the centre). *Left*: R-filter image with a resolution of 1.3″ taken with the INT/WFC. *Right*: image taken by CoRoT, at the same scale and orientation. The jagged outline in its center is the photometric aperture mask; indicated are also CoRoT's x and y image coordinates and positions of nearby stars from the Exo-Dat (Deleuil et al. 2009) database.

Using the method describe by Deeg et al. (2009), the fraction of contamination in the CoRoT-12 photometric aperture mask was estimated to be 3.3 ± 0.5%. It is mostly due to a 3.5 mag fainter star that is 8.5″ SW. This small dilution was taken into account in our analysis presented in Sect. 5.

3.2. Radial velocities – spectroscopy

Four radial velocity (RV) measurements were obtained with the HARPS spectrograph (Pepe et al. 2002; Mayor et al. 2003) on the 3.6-m telescope at ESO La Silla Observatory (Chile), on October 2008 (HARPS program 082.C-0120). These first data were made using the high efficiency mode EGGS in order to establish the planetary nature of the companion, showing a detectable and low-amplitude radial velocity variation in phase with the CoRoT ephemeris, with the shortest exposure time. Ten additionnal measurements were recorded with HARPS, from November 27, 2009 to February 05, 2010 (HARPS program 184.C-0639). These newer data points were acquired using the high accuracy mode HAM to increase the precision of the RV measurements compared to the about 30 $\mathrm{m\,s^{-1}}$ of systematic errors of the high efficiency mode (Moutou et al. 2009), and without simultaneous thorium (obj_AB mode) in order to monitor the Moon background light on the second fiber B. Radial velocities were obtained from the HARPS spectra by computing weighted cross-correlation with a numerical G2 mask (Baranne et al. 1996; Pepe et al. 2002).

Sixteen spectra of CoRoT-12 were also acquired with the HIRES spectrograph on the Keck I telescope as part of NASA's key science project in support of the CoRoT mission. Differential RVs were computed from these spectra with the *Austral* code (Endl et al. 2000). First, ten spectra were gathered during a transit of CoRoT-12b in January 2009. Unfortunately, the used set-up of the slit decker did not allow a proper subtraction of the sky background, leading to RV systematics with an amplitude of a few dozens $\mathrm{m\ s^{-1}}$, so we decided to reject these data. Six other HIRES RVs were obtained between December 2009 and January 2010. For these six spectra, the set-up of the slit decker was changed, leading to a proper background subtraction.

Our HARPS and HIRES measurements are presented in Table 2. An orbital analysis was performed treating the three sets of RV measurements (HARPS HAM, HARPS EGGS, and HIRES) as independent data sets with different zero point velocities. The orbital solution was made keeping the period and ephemeris fixed to the CoRoT values, but allowing the zero point offsets to be fit in a least square way. Figure 3 shows the resulting orbital solution which is in phase with the CoRoT photometric signal. The resulting eccentricity (0.03 ± 0.13) was consistent with zero while the semi-amplitude was 124 ± 15 $\mathrm{m\,s^{-1}}$. Assuming a solar-mass host star, this semi-amplitude translates into a transiting object with a mass of about 0.9 M_J. In Sect. 5 we present a revised orbit obtained using a global analysis.

The residual RVs were analyzed after removing the orbit to look for the possible presence of additional companions. No significant variations were found, but given the sparseness of the measurements we cannot exclude the presence of additional companions with a good confidence.

The HARPS cross-correlation functions were analyzed using the line-bisector technique (Queloz et al. 2000). Figure 4 shows the correlation between the bisector and RV measurements. The correlation coeffient of all the RV-bisector measurements, r, has a value of 0.56 with a probability 0.026 that the data is uncorrelated. Ostensibly this correlation looks to be significant, but we do not believe that to be the case as this correlation is largely driven by one outlier in the HARPS data and another EGGS measurement. When one examines only the HARPS data the coefficient drops to $r = 0.47$ with a probabilty of 0.15 that the data is uncorrelated. Removing one outlier point lowers the correlation coefficient to $r = 0.32$ with the probability of no correlation being 0.37.

We believe that the modestly high correlation coefficient may be an artifact of the bisector error being more than a factor of two larger than the RV measurement error and the paucity of measurements. To test this we generated fake bisector/RV data consisting only of random noise that was sampled the same way as the real data. The standard deviations of the fake measurements were consistent with the median error of the RV and bisector measurements. In approximately 40% of the cases the correlation coefficient of these random data had correlation coefficients at least as large as that of the real data. The RV-bisector correlation coefficient that we measure is consistent with random noise coupled with sparse sampling. This discards the possibility that the periodic signal detected in these RVs is caused by a blended eclipsing binary. Taking into account the fact that CoRoT-12 is a solar analog star (see Sect. 4), we interpret thus the eclipses detected in CoRoT photometry as transits of a new giant planet, CoRoT-12b.

Table 2. HARPS and HIRES radial velocity measurements for CoRoT-12.

HJD (days)	RV ($\mathrm{km\,s^{-1}}$)	σ_RV ($\mathrm{km\,s^{-1}}$)	Bisector ($\mathrm{km\,s^{-1}}$)
HARPS EGGS			
2 454 745.86036	12.1740	0.0221	–0.0256
2 454 746.83735	11.9341	0.0369	–0.1307
2 454 747.86641	12.0904	0.0198	–0.0320
2 454 763.81411	11.9856	0.0121	–0.0435
HARPS HAM			
2 455 163.73528	12.1193	0.0458	0.0429
2 455 165.71941	11.9857	0.0263	–0.0310
2 455 167.72180	12.0570	0.0342	0.0105
2 455 219.63940	12.0051	0.0195	–0.0111
2 455 220.68849	12.2435	0.0167	–0.0188
2 455 226.66329	12.2126	0.0168	0.0246
2 455 227.68971	12.0348	0.0442	0.0335
2 455 229.64150	12.2355	0.0292	0.0259
2 455 231.68894	12.1640	0.0240	0.0167
2 455 233.60091	11.9993	0.0292	–0.0945
HIRES			
2 455 170.99823	–0.0573	0.0286	
2 455 223.00984	0.0490	0.0144	
2 455 223.02060	0.0466	0.0144	
2 455 223.98643	0.1633	0.0143	
2 455 224.93395	–0.0659	0.0175	
2 455 224.94528	–0.0979	0.0220	

Notes. The HARPS RVs are absolute, while the HIRES RVs are differential (measured relative to a stellar template). The bisectors were not measured from the HIRES spectra.

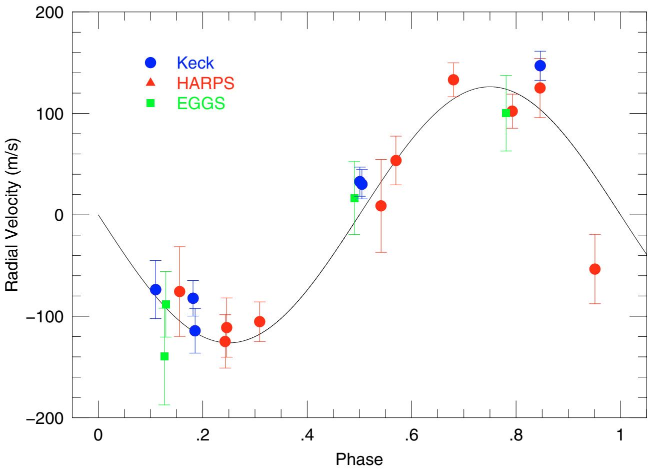

Fig. 3. HARPS and HIRES RVs phase-folded on the CoRoT ephemeris and overimposed on the best fit orbital model.

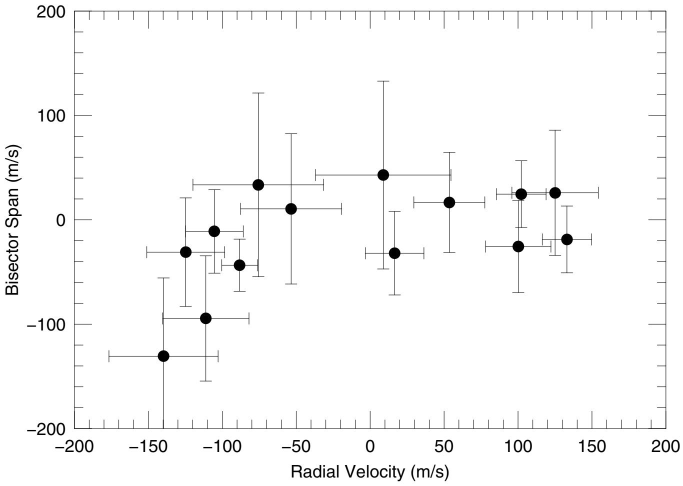

Fig. 4. Bisector versus RV measured from the HARPS spectra. Errors of twice the RV errors were adopted for all the bisector measurements.

Table 3. Stellar parameters and elemental abundances derived for CoRoT-12 from our VWA spectroscopic analysis.

$T_{\rm eff}$	5675 ± 80 K
$\log g$	4.52 ± 0.08
$v_{\rm mic}$	0.6 ± 0.2 km s^{-1}
$v_{\rm mac}$	1.5 ± 0.3 km s^{-1}
$v \sin i$	1.0 ± 1.0 km s^{-1}
d	1150 ± 85 pc
[Fe/H]	0.16 ± 0.10
[Na/H]	0.17 ± 0.06
[Mg/H]	0.13 ± 0.07
[Al/H]	0.15 ± 0.10
[Si/H]	0.12 ± 0.08
[Ca/H]	0.09 ± 0.10
[Sc/H]	0.22 ± 0.15
[Ti/H]	0.05 ± 0.09
[V/H]	0.02 ± 0.08
[Cr/H]	0.17 ± 0.09
[Mn/H]	0.20 ± 0.13
[Co/H]	0.16 ± 0.14
[Ni/H]	0.21 ± 0.08

4. Stellar parameters

Two master spectra were used to determine the atmospheric parameters of the star. The first of them was made by co-addition of the seven HARPS HAM spectra which were not strongly contamined by the Moon background light. The resulting master spectrum had a signal-to-noise ratio (SNR) about 40 in the continuum. The second master spectrum was obtained from the co-addition of two Keck spectra and had a SNR about 100 in the continuum.

The methodology used to analyze these two master spectra was mainly based on the semi-automatic package VWA (Bruntt et al. 2002, 2008, 2010), and is thoroughly described by Deleuil et al. (2008) and Bruntt et al. (2010). The derived atmospheric parameters and elemental abundances are presented in Table 3.

The Li I line at 670.78 nm was not detected in both master spectra, nor any hint of chromospheric activity. From this, the low rotational velocity measured in the spectra, and the low photometric variability noticed in the CoRoT LC, CoRoT-12 appears thus to be a quiet and slowly rotating solar analog star.

Using $T_{\rm eff}$ and $\log g$ from the VWA spectroscopic analysis, we estimated the absolute magnitude $M_V \simeq 4.75$ mag and colour excess $E(J-K) \simeq 0.08$ mag from the Allen's tables (Cox 2000). We calculated the corresponding interstellar absorption $A_V \simeq 0.46$ (using $A_V = (5.82 \pm 0.1) \times E(J-K)$; Cox 2000), to estimate, with the V apparent magnitude, the distance of the star to be $d = 1150 \pm 85$ pc.

5. Global analysis

5.1. Description

We performed a thorough global analysis of the CoRoT transit photometry and HARPS/HIRES RVs to get the strongest constraints on the system parameters. First, we cut the parts of the CoRoT LC located within 0.15 days of the transit mid-times deduced from the preliminary transit ephemeris presented in Sect. 2, getting thus 47 individual transit LCs. Considering their large number of measurements, we decided to stack the measurements of the 36 over-sampled transit LCs per 4, to speed-up our analysis. This binning did not affect our final precision on the system parameters, as the resulting folded LC (see Fig. 5) is still well sampled.

Our analysis was done with the adaptative Markov Chain Monte-Carlo (MCMC) algorithm presented by Gillon et al. (2009, 2010). MCMC is a Bayesian inference method based on stochastic simulations that samples the posterior probability distributions of adjusted parameters for a given model. Our MCMC implementation uses the Metropolis-Hasting algorithm (see, e.g., Carlin & Louis 2008) to perform this sampling. Our nominal model was based on a star and a transiting planet on a Keplerian orbit about their center of mass. More specifically, we used a classical Keplerian model for the RVs, while we modeled the eclipse photometry with the photometric eclipse model of Mandel & Agol (2002) multiplied by a baseline model consisting of a different fourth-order time polynomial for each of the 47 CoRoT time-series. The coefficients of these baseline models were determined by least-square minimization at each steps of the Markov chains (see Gillon et al. 2010, for details).

Our analysis was composed of a nominal MCMC run, followed by two other MCMC runs having different specificities that are described below and summarized in Table 4. Each of the MCMC runs was composed of five Markov chains of 10^5 steps, the first 20% of each chain being considered as its burn-in phase and discarded. For each run, the convergence of the five Markov chains was checked using the statistical test presented by Gelman & Rubin (1992).

The correlated noise present in the LCs was taken into account as described by Gillon et al. (2010), i.e., a scaling factor was determined for each LC from the standard deviation of the binned and unbinned residuals of a preliminary MCMC analysis, and it was applied to the error bars (see also Winn et al. 2008). For the RVs, a "jitter" noise of 5 m s^{-1} was added quadratically to the error bars, this value being an upper limit for a quiet solar-type star like CoRoT-12 (Wright 2005). Practically, this low jitter noise has no impact on the posterior distributions of the system parameters, as CoRoT-12 is faint and the RV precision is photon noise/background contamination limited. For the four HARPS measurements obtained with the EGGS mode, a systematic error of 30 m s^{-1} was also added quadratically to the error bars (see Sect. 3.2).

In all three MCMC runs, the following parameters were jump parameters[2]: the planet/star area ratio $(R_{\rm p}/R_{\rm s})^2$, the transit

[2] Jump parameters are the parameters that are randomly perturbed at each step of the MCMC.

Table 4. Specificities of the three MCMC runs performed during our global analysis. See text for details.

	Data	Jump parameters	Normal prior distributions
$MCMC_1$	CoRoT transits	$(R_p/R_s)^2$, W, b',	$u_1 \sim N(0.47, 0.03^2)$
	HARPS (EGGS+HAM)	P, T_0, K_2, c_1, c_2,	$u_2 \sim N(0.22, 0.02^2)$
	HIRES (not transit)	$e\cos\omega$, $e\sin\omega$	
$MCMC_2$	idem $MCMC_1$	idem $MCMC_1$	$u_1 \sim N(0.47, 0.03^2)$
	+ CoRoT occultations	+ occultation depth dF_2	$u_2 \sim N(0.22, 0.02^2)$
$MCMC_3$	idem $MCMC_1$	idem $MCMC_1$	$u_1 \sim N(0.47, 0.03^2)$
		+ 47 TTVs	$u_2 \sim N(0.22, 0.02^2)$
			$TTV_{i\in[1:47]} \sim N(0, \sigma^2_{TT,i})$

width (from first to last contact) W, the parameter $b' = a\cos i/R_*$ (which is the transit impact parameter in case of a circular orbit), the orbital period P and time of minimum light T_0, the two Lagrangian parameters $e\cos\omega$ and $e\sin\omega$ where e is the orbital eccentricity and ω is the argument of periastron, and the parameter $K_2 = K\sqrt{1-e^2}\,P^{1/3}$, where K is the RV orbital semi-amplitude (see Gillon et al. 2009, 2010). We assumed a uniform prior distribution for all these jump parameters. To take into account the small dilution of the signal due to contaminating stars (see Sect. 3.1), the jump parameters $(R_p/R_s)^2$ was divided at each step of the MCMC by a number drawn from the distribution $N(1.033, 0.005^2)$ before being used in the computation of the eclipse model.

We did not assume a perfectly circular orbit in any of our MCMC runs despite that a circular orbit is compatible with the results of our orbital analysis of the RVs (see Sect. 3.2). Indeed, most short-period planets could keep a tiny but non-zero eccentricity during a major part of their lifetime (Jackson et al. 2008), so fixing the eccentricity to zero is not justified by tidal theory and could lead to overoptimistic error bars on the system parameters.

We assumed a quadratic limb-darkening law, and we allowed the quadratic coefficients u_1 and u_2 to float in our MCMC runs, using as jump parameters not these coefficients themselves but the combinations $c_1 = 2\times u_1 + u_2$ and $c_2 = u_1 - 2\times u_2$ to minimize the correlation of the obtained uncertainties (Holman et al. 2006). To obtain a limb-darkening solution consistent with theory, we decided to use normal prior distributions for u_1 and u_2 based on theoretical values. Sing (2010) presented recently a grid of limb-darkening coefficients specially computed for the CoRoT non-standard bandpass and for several limb-darkening laws. We deduced the values $u_1 = 0.47 \pm 0.03$ and $u_2 = 0.22 \pm 0.02$ from Sing's grid for the spectroscopic parameters of CoRoT-12 and their errors (Table 3). The corresponding normal distributions $N(0.47, 0.03^2)$ and $N(0.22, 0.02^2)$ were used as prior distributions for u_1 and u_2 in our MCMC analysis.

At each step of the Markov chains, the stellar density deduced from the jump parameters, and values for $T_{\rm eff}$ and [Fe/H] drawn from the normal distributions deduced from our spectroscopic analysis, were used as input for the stellar mass calibration law deduced by Torres et al. (2010) from well-constrained detached binary systems[3]. Using the resulting stellar mass, the physical parameters of the system were then deduced from the jump parameters at each MCMC step. To account for the uncertainty on the parameters of the stellar calibration law, the values for these parameters were randomly drawn at each step of the Markov chains from the normal distribution presented by Torres et al. (2010).

In our second MCMC run (labeled $MCMC_2$ in Table 4), we also used as data the parts of the CoRoT LC located within 0.2 days of the *occultation* mid-times deduced from the best fit transit ephemeris of our nominal $MCMC$ run. The goal of this run was to obtain an upper limit for the depth of the occultation in the CoRoT photometry. For this run, the occultation depth was thus also a jump parameter.

Finally, we assessed the perfect periodicity of the transits of CoRoT-12b in our third run (labeled $MCMC_3$ in Table 4). For this run, a transit timing variation (TTV) was considered as jump parameter for each of the 47 transits. Obviously, the orbital period could not be determined unambiguously without any prior on these TTVs, so we assumed a normal prior distribution centered on zero for each of them. Practically, we added the following Bayesian penalty to our merit function:

$$BP_{\rm timings} = \sum_{i=1,47}\left(\frac{TTV_i}{\sigma_{TT_i}}\right)^2 \tag{1}$$

where TTV_i is the TTV for the ith CoRoT transit, and σ_{TT_i} is the error on its timing estimated by a preliminary individual analysis of this transit.

5.2. Results

Table 5 present the CoRoT-12 system parameters and 1-σ error limits derived from our nominal MCMC run ($MCMC_1$), and for the two other MCMC runs.

Our MCMC analysis presents CoRoT-12b as an inflated Jupiter-mass planet ($M_p = 0.92 \pm 0.07\ M_{\rm Jup}$, $R_p = 1.44 \pm 0.13\ R_{\rm Jup}$) transiting a solar analog star ($M_* = 1.08 \pm 0.08\ M_\odot$, $R_* = 1.1 \pm 0.1\ R_\odot$). Using the stellar density deduced from our MCMC analysis ($\rho_* = 0.77^{+0.20}_{-0.15}\ \rho_\odot$) and the effective temperature and metallicity obtained from spectroscopy (Table 3), a stellar evolution modeling based on the code CLES (Scuflaire et al. 2008) leaded to a stellar mass of $1.07 \pm 0.10\ M_\odot$, in excellent agreement with our MCMC result, and to a poorly constrained age of 6.3 ± 3.1 Gyr. It is also worth noticing that the two independent values obtained for the stellar surface gravity from our spectroscopic and global analysis are in good agreement (1.4σ), indicating the good coherence of our final solution.

Figure 5 presents the period-folded CoRoT photometry binned per two minutes time intervals with the best fit transit model superimposed. The standard deviation of the residuals of this latter LC is 592 ppm, demonstrating the excellent quality of the CoRoT photometry.

[3] The stellar calibration law presented by Torres et al. is in fact function of $T_{\rm eff}$, [Fe/H] and $\log g$. We modified it to use as input the stellar density instead of the stellar surface gravity (see Anderson et al. 2010b).

Table 5. Median and 1-σ limits of the posterior distributions obtained for the CoRoT-12 system derived from our three MCMC runs (see Table 4).

Parameter	$MCMC_1$	$MCMC_2$	$MCMC_3$
Jump parameters			
Planet/star area ratio $(R_p/R_s)^2$	$0.01744^{+0.00039}_{-0.00040}$	$0.01739^{+0.00044}_{-0.00041}$	$0.01735^{+0.00044}_{-0.00043}$
$b' = a\cos i/R_*$ [R_*]	$0.609^{+0.055}_{-0.057}$	$0.614^{+0.060}_{-0.056}$	$0.592^{+0.040}_{-0.046}$
Transit width W [d]	$0.10726^{+0.00089}_{-0.00090}$	$0.1071^{+0.0013}_{-0.0011}$	$0.1071^{+0.0011}_{-0.0013}$
$T_0 - 2450000$ [HJD]	4398.62707 ± 0.00036	$4398.62704^{+0.00038}_{-0.00036}$	$4398.6266^{+0.0013}_{-0.0012}$
Orbital period P [d]	2.828042 ± 0.000013	$2.828043^{+0.000013}_{-0.000014}$	$2.828061^{+0.000052}_{-0.000047}$
RV K_2 [m s^{-1} d$^{1/3}$]	177^{+12}_{-11}	176 ± 11	177 ± 10
$e\cos\omega$	$-0.012^{+0.024}_{-0.028}$	$0.000^{+0.020}_{-0.040}$	$-0.017^{+0.024}_{-0.026}$
$e\sin\omega$	$0.053^{+0.073}_{-0.066}$	$0.069^{+0.069}_{-0.082}$	$0.043^{+0.072}_{-0.053}$
c_1	1.152 ± 0.056	$1.153^{+0.054}_{-0.059}$	$1.146^{+0.058}_{-0.050}$
c_2	0.028 ± 0.052	$0.031^{+0.052}_{-0.051}$	$0.027^{+0.048}_{-0.049}$
dF_2		$0.00009^{+0.00022}_{-0.00009}$	
Deduced stellar parameters			
u_1	0.466 ± 0.027	$0.468^{+0.026}_{-0.029}$	$0.464^{+0.028}_{-0.025}$
u_2	0.219 ± 0.021	0.217 ± 0.020	$0.219^{+0.020}_{-0.019}$
Density ρ_* [$\rho_\odot$]	$0.77^{+0.20}_{-0.15}$	$0.75^{+0.20}_{-0.15}$	$0.81^{+0.18}_{-0.12}$
Surface gravity $\log g_*$ [cgs]	$4.375^{+0.065}_{-0.062}$	$4.366^{+0.066}_{-0.063}$	$4.388^{+0.055}_{-0.046}$
Mass M_* [$M_\odot$]	$1.078^{+0.077}_{-0.072}$	$1.083^{+0.075}_{-0.074}$	$1.076^{+0.077}_{-0.071}$
Radius R_* [$R_\odot$]	$1.116^{+0.096}_{-0.092}$	$1.129^{+0.097}_{-0.092}$	$1.098^{+0.072}_{-0.076}$
Deduced planet parameters			
RV K [m s^{-1}]	$125.5^{+8.0}_{-7.5}$	$125.4^{+7.4}_{-7.7}$	125.5 ± 7.1
$b_{transit}$ [R_*]	$0.573^{+0.027}_{-0.030}$	$0.571^{+0.031}_{-0.033}$	$0.564^{+0.033}_{-0.038}$
$b_{occultation}$ [R_*]	$0.64^{+0.10}_{-0.09}$	$0.65^{+0.11}_{-0.09}$	$0.620^{+0.071}_{-0.078}$
$T_{occultation} - 2450000$ [HJD]	$4400.020^{+0.055}_{-0.052}$	$4400.041^{+0.036}_{-0.073}$	$4400.010^{+0.043}_{-0.048}$
Orbital semi-major axis a [AU]	$0.04016^{+0.00093}_{-0.00092}$	$0.04022^{+0.00091}_{-0.00093}$	$0.04013^{+0.00094}_{-0.00090}$
Orbital inclination i [deg]	$85.48^{+0.72}_{-0.77}$	$85.39^{+0.72}_{-0.84}$	$85.67^{+0.59}_{-0.51}$
Orbital eccentricity e	$0.070^{+0.063}_{-0.042}$	$0.083^{+0.062}_{-0.047}$	$0.059^{+0.061}_{-0.031}$
Argument of periastron ω [deg]	105^{+90}_{-27}	87^{+33}_{-88}	113^{+92}_{-26}
Equilibrium temperature T_{eq} [K][a]	1442 ± 58	1449^{+60}_{-58}	1431 ± 47
Density ρ_p [ρ_{Jup}]	$0.309^{+0.097}_{-0.071}$	$0.298^{+0.093}_{-0.069}$	$0.327^{+0.082}_{-0.058}$
Surface gravity $\log g_p$ [cgs]	$3.043^{+0.082}_{-0.080}$	$3.031^{+0.083}_{-0.077}$	$3.060^{+0.065}_{-0.063}$
Mass M_p [M_{Jup}]	$0.917^{+0.070}_{-0.065}$	$0.916^{+0.068}_{-0.064}$	$0.915^{+0.068}_{-0.064}$
Radius R_p [R_{Jup}]	1.44 ± 0.13	$1.45^{+0.13}_{-0.12}$	$1.41^{+0.10}_{-0.09}$

Notes. $MCMC_1$ is our nominal analysis (see text for details). [a] Assuming $A = 0$ and $F = 1$.

Our results show that the limb-darkening coefficients u_1 and u_2 are poorly constrained by the CoRoT transit photometry, despite its good precision. Indeed, the posterior distributions of u_1 and u_2 are close to the prior distributions, indicating that the CoRoT data do not constrain these parameters much.

Our final precisions on the stellar and planetary masses and radii are not excellent (about 7% on the masses and about 10% on the radii), and more observations are required to thoroughly characterize this system. In this context, improving significantly the precision on the stellar density (about 20%) is desirable. Such an improvement could be achieved mostly through a better characterization of the orbital parameters $e\cos\omega$ and $e\sin\omega$ with more RV measurements (and possibly occultation photometry). Indeed, an new MCMC analysis assuming a perfectly circular orbit leads >2 times smaller error bars on the planet's and star's radii. The characterization of the system would also benefit from an improved determination of the transit parameters with more high-precision transit photometry, if possible acquired in a redder bandpass (less significant limb-darkening).

The results of the run $MCMC_2$ show that the occultation of the planet is not detected in the CoRoT data. We can only put an upper limit on its depth (3-σ upper limit = 680 ppm).

As expected, the errors on T_0 and P are significantly larger for the run $MCMC_3$, but the posterior distributions obtained for the other parameters agree well with ones of the other MCMC runs. The resulting TTVs are shown in Fig. 6. No transit shows a significant timing variation. Still, the resulting TTV series seems to show a correlated structure. Fitting a sinusoidal function in this series leads to a best-fit period of about 24 epochs, i.e. of about 68 days. Nevertheless, the resulting false alarm probability is high, about 15%, indicating that this correlated structure is not very significant. Still, it is interesting to notice that, if we

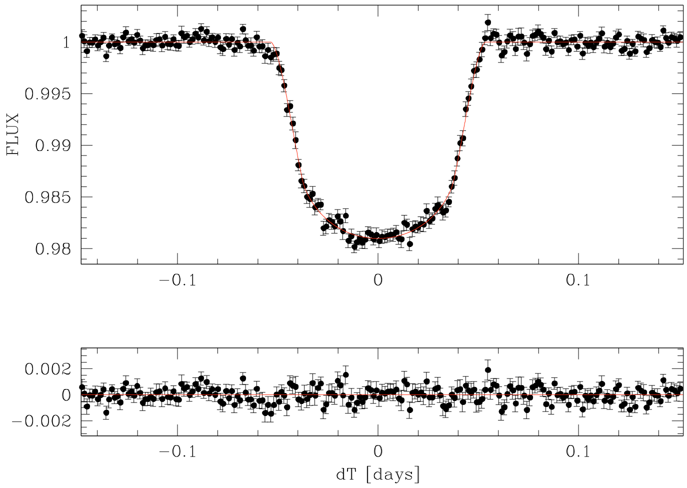

Fig. 5. *Top*: CoRoT transit photometry period-folded and binned per 2 minutes time intervals, with the best fit transit model superimposed. *Bottom*: residuals. Their standard deviation is 592 ppm.

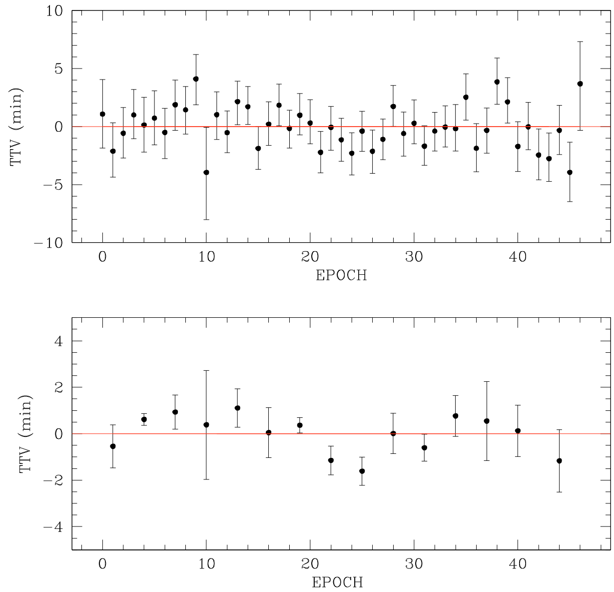

Fig. 6. *Top*: median value and 1-σ limits of the TTV posterior distributions obtained in $MCMC_3$. *Bottom*: same curve obtained after binning the TTVs per three (error of each bin = error on the mean).

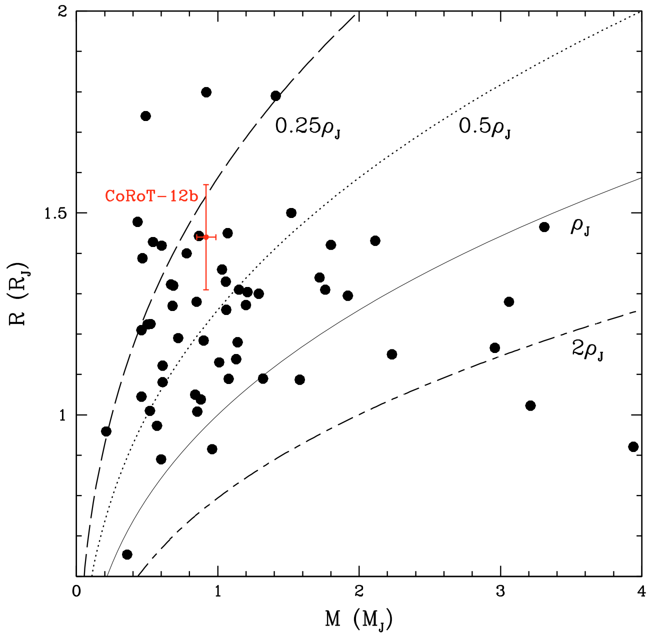

Fig. 7. Position of CoRoT-12b (in red) among the other transiting planets (black circles, values from http://exoplanet.eu) in a mass-radius diagram. The error bars are shown only for CoRoT-12b (C12), WASP-17b (W17), TrES-4b (T4), and WASP-12b (W12) for the sake of clarity.

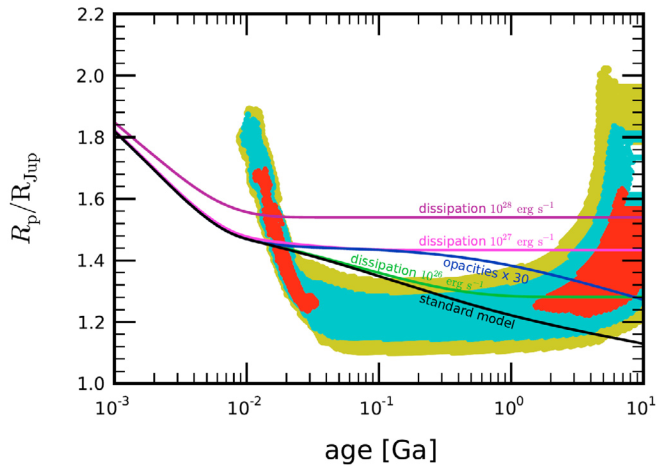

Fig. 8. Evolution of the size of CoRoT-12b (in Jupiter units, $R_{\rm Jup}$) as a function of age (in billion years), compared to constraints inferred from CoRoT photometry, spectroscopy, radial velocimetry and CESAM stellar evolution models. Red, blue and yellow-green dots correspond to the planetary radii and ages that result from stellar evolution models matching the inferred ρ_*-$T_{\rm eff}$ uncertainty ellipse within 1σ, 2σ and 3σ, respectively. Planetary evolution models for a planet with a solar-composition envelope and no core are shown as plain lines and are labeled as follow: *standard (black)*: irradiated planet with no extra heat source; *opacities x 30 (blue)*: opacities have been artificially multiplied by 30 compared to standard model; *dissipation*: models in which 10^{26} (*green*), 10^{27} (*pink*), and 10^{28} (*purple*) erg s^{-1} is deposited at the planet's center. These models assume a total mass of 0.92 $M_{\rm Jup}$ and an equilibrium temperature of 1450 K

assume a rotational period of 68 days for the star and $\sin i = 1$, and using $R_* = 1.1\ R_\odot$, we obtain a value of 1.2 km s^{-1} for $v \sin i$, in excellent agreement with the value derived from our spectroscopic analysis (see Table 3). In this context, a possible interpretation of the low-amplitude structure visible in the TTV series is that it is caused by the rotation of the surface of the star and its influence on the transit barycenters.

6. Discussion

The position of CoRoT-12b in a planetary mass-radius diagram is shown in Fig. 7. While being denser than the extremely inflated planets WASP-17b (Anderson et al. 2010a), TrES-4b (Mandushev et al. 2007) and WASP-12b (Hebb et al. 2009), CoRoT-12b appears to be a very low-density "hot Jupiter". Using the hypothesis that the planet is a core-less gazeous planet of solar composition, we used the planetary evolution code CEPAN (Guillot & Morel 1995) to assess the ability of standard irradiated planet models to explain the low-density of CoRoT-12b. Several models were used: a standard model with no extra heat source, a model for which the opacities were artificially multiplied by 30, and three models with a constant energy deposit (10^{26}, 10^{27} and 10^{28} erg s^{-1}) at the planet's center. Our results in terms of planetary size evolutions are shown in Fig. 8.

For recall, we constrain the age of the system to 6.3 ± 3.1 Gyr. Considering this age, the measured size of CoRoT-12b is in good agreement with all four evolution models. At most can we notice that an extra heat source and/or of larger opacities are favored by the data, but a more precise radius measurement is needed to conclude.

In this context, it is worth noticing that the precision on the planet's radius is mostly limited by the precision on the orbital eccentricity and argument of periastron (see Sect. 5.2). It is thus desirable to obtain more RV measurements of the system. Better constraining the planet's orbital eccentricity would also make possible the assessment of its past tidal evolution and its influence on its energy budget (e.g., Ibgui et al. 2010).

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References

Alonso, R., Auvergne, M., Baglin, A., et al. 2008, A&A, 482, L21
Anderson, D. R., Hellier, C., Gillon, M., et al. 2010a, ApJ, 709, 159
Anderson, D. R., Gillon, M., Maxted, P. F. L., et al. 2010b, A&A, 513, L3
Auvergne, M., Bodin, P., Boisnard, L., et al. 2009, A&A, 506, 411
Baglin, A., Auvergne, M., Barge, P., et al. 2009, Transiting Planets, Proceedings of the International Astronomical Union, IAU Symp., 253, 71
Baranne, A., Queloz, D., Mayor, M., et al. 1996, A&AS, 119, 373
Barge, P., Baglin, A., Auvergne, M., et al. 2008, A&A, 482, L17
Bruntt, H.,Catala, C., Garrido, R., et al. 2002, A&A, 389, 345
Bruntt, H., De Cat, P., & Aerts, C. 2008, A&A, 478, 487
Bruntt, H., Deleuil, M., Fridlund, M., et al. 2010, A&A, 519, A51
Carlin, B. P., & Louis, T. A. 2008, Bayesian Methods for Data Analysis, 3rd edn. (Chapman & Hall/CRC)
Claret, A. 2000, A&A, 363, 1081
Claret, A. 2004, A&A, 428, 1001
Cox, A. N. 2000, Allen's Astrophysical Quantities (AIP Press, Springer)
Deeg, H. J., Gillon, M., Shporer, A., et al. 2009, A&A, 506, 343
Deeg, H. J., Moutou, C., Eriksson, A., et al. 2010, Nature, 464, 384
Deleuil, M., Deeg, H. J., Alonso, R., et al. 2008, A&A, 491, 889
Deleuil, M., Meunier, J. C., Moutou, C., et al. 2009, AJ, 138, 649
Deming, D., & Seager, S. 2009, Nature, 462, 302
Endl, M., Kürster, M., & Els, S. 2000, A&A, 363, 585
Gelman, A., & Rubin, D. 1992, Statist. Sci., 7, 457
Gillon, M., Demory, B.-O., Triaud, A. H. M. J., et al. 2009, A&A, 506, 359
Gillon, M., Lanotte, A. A., Barman, T., et al. 2010, A&A, 511, 3
Giménez, A. 2006, ApJ, 650, 408
Guillot, T., & Morel, P. 1995, A&AS, 109, 109
Hebb, L., Collier-Cameron, A., Loeillet, B., et al. 2009, ApJ, 693, 1920
Holman, M. J., Winn, J. N., Latham, D. W., et al. 2006, ApJ, 652, 1715
Ibgui, L., Burrows, A., & Spiegel, D. S. 2010, ApJ, 713, 751
Jackson, B., Greenberg, R., & Barnes, R. 2008, ApJ, 681, 1631
Léger, A., Rouan, D., Schneider, J., et al. 2009, A&A, 506, 287
Mandel, K., & Agol, E. 2002, ApJ, 580, 171
Mandushev, G., OĎonovan, F. T., Charbonneau, D., et al. 2007, ApJ, 667, L195
Mayor,, M., Pepe,, F., Queloz,, D., et al. 2003, The Messenger, 114, 20
Moutou, C., Pont, F., Bouchy, F., et al. 2009, A&A, 506, 321
Pepe, F., Mayor, M., Galland, F., et al. 2002a, A&A, 388, 632
Pepe, F., Mayor, M., Rupprecht, G., et al. 2002b, The Messenger, 110, 9
Queloz, D., Eggenberger, A., Mayor, M., et al. 2000, A&A, 359, L13
Queloz, D., Bouchy, F., Moutou, C., et al. 2009, A&A, 506, 303
Rauer, H., Queloz, D., Csizmadia, Sz, et al. 2009, A&A, 506, 281
Scuflaire, R., Théado, S., Montalbán, J., et al., 2008, APSS, 316, 83
Sing, D. K. 2010, A&A, 510, 21
Skrustkie, M. F., Cutri, R. M., Stiening, M. D., et al. 2006, AJ, 131, 1163
Surace, C., Alonso, R., Barge, P., et al. 2008, Proceedings of the SPIE, 7019
Torres, G., Andersen, J., & Giménez, A. 2010, A&ARv, 18, 67
Winn, J. N., Holman, M. J., Torres, T., et al. 2008, ApJ, 683, 1076
Winn, J. N. 2010, to appear in Exoplanets, ed. S. Seager (Tucson: University of Arizona Press) [arXiv:1001.2010]
Wright J. T. 2005, PASP, 117, 657

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