Transiting exoplanets from the \textit{CoRoT} space mission*

XV. CoRoT-15b: a brown dwarf transiting companion

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Received ; accepted

ABSTRACT

We report the discovery by the \textit{CoRoT} space mission of a transiting brown dwarf orbiting a F7V star with an orbital period of 3.06 days. CoRoT-15b has a radius of 1.12 ± 0.026 \(R_{\odot}\), a mass of 63.3 ± 4.1 \(M_{\odot}\), and is thus the second transiting companion lying in the theoretical mass domain of brown dwarfs. CoRoT-15b is either very young or inflated compared to standard evolution models, a situation similar to that of M-dwarfs stars orbiting close to solar-type stars. Spectroscopic constraints and an analysis of the lightcurve favors a spin period between 2.9 and 3.1 days for the central star, compatible with a double-synchronisation of the system.

Key words. brown dwarfs - planetary systems - low-mass - techniques: photometry - techniques: radial velocities - techniques: spectroscopic

1. Introduction

The \textit{CoRoT} space mission (Baglin et al. 2009), in operation since the start of 2007 and extended to the end of 2013, is designed to find transiting exoplanets. A natural product of this mission is that any object with size of Jupiter or lower that transits its host star can be detected. This includes stellar and sub-stellar companions such as M-dwarfs and brown dwarfs (BDs). In the mass-radius diagram of transiting companions orbiting solar-type stars, there is up until now only one known brown-dwarf, CoRoT-3b (Deleuil et al. 2008), located in the gap in mass between planetary and low-mass star companions. Determination of the physical properties of such objects are fundamental to understand the link between the population of planets and low-mass stars and to distinguish the formation and evolution processes of the two populations.

We report in this paper the discovery of a new transiting brown-dwarf by \textit{CoRoT} established and characterized thanks to ground-based follow-up observations. CoRoT-15b, with an estimated radius of 1.12 \(R_{\odot}\) and an estimated mass of 63.3 \(M_{\odot}\), orbits in 3.06 days an F-type dwarf with solar metallicity.

2. \textit{CoRoT} observations

SRa02 was the seventh field observed with \textit{CoRoT} in the second year after its launch. It corresponds to the third short run and was located towards the so-called galactic anti-center direction. This run started on 2008 October 11 and ended on 2008 November 12, constituting of a total of 31.7 days of almost-continuous observations.

More than 30 multi-transiting candidates for planets were found among the 10265 targets of the SRa02 field. About half of them were clearly identified as binaries from light-curve analysis and around tenth of high priority planet-size candidates were selected in this short run including SRa02_E14106 afterwards called CoRoT-15. The various ID of this target, including coordinates and magnitudes are listed in table [I].

3. \textit{CoRoT} light curve analysis

CoRoT-15, with an estimated V magnitude close to 16, is located at the faint end of the stellar population observed by \textit{CoRoT}. In this magnitude domain, the signal is not sufficient to split the photometric aperture in three colors and the extracted lightcurve, also called white lightcurve, is monochromatic (Llebaria & Guterman 2006). The sampling rate was at 512 seconds during the whole run and not oversampled to 32 seconds since this candidate was not identified with the alarm mode (Surace et al. 2008). Fig. [I] shows the lightcurve of CoRoT-15 delivered by the N2 data levels pipeline. This lightcurve is quite noisy and is affected by several high energy particles impacts which result in hot pixels as well as possible stellar variability.
Table 1. IDs, coordinates and magnitudes.

| CoRoT window ID | CoRoT ID | USNO-B1 ID | 2MASS ID |
|-----------------|----------|------------|----------|
| SRat02_E1_4106  | 221686194| 0961-0097866| 06282781-0611105|
| RA (J2000)      | 06:28:27.82| +06:11:10.47 |
| Dec (J2000)     | 06:28:27.82| +06:11:10.47 |
| B1              | 16.85    |            |          |
| B2              | 16.59    |            |          |
| R1              | 15.47    |            |          |
| R2              | 15.43    |            |          |
| I               | 14.83    |            |          |
| J               | 13.80 ± 0.026 |          |
| H               | 13.42 ± 0.037 |          |
| K               | 13.389 ± 0.050 |          |

a from USNO-B1 catalog
b from 2MASS catalog

Fig. 1. Raw light curve of CoRoT-15.

A first analysis of the light curve (LC), based on a trapezoidal fit to each individual transit, reveals periodic transits with depth of 0.68% and a period of 3.0608 ± 0.0008 days.

Since the CoRoT lightcurve is relatively noisy, no meaningful limits to either the visible-light albedo of the companion nor to its dayside surface temperature could be established.

From the raw lightcurve, we tried to estimate the stellar rotation period. We filtered out variations with timescales shorter than 15 data points (~2.13h) to reduce sensitivity to the satellite orbital effects and other short term variations, and we then removed the transits. The computed LS periodogram appears to be quite noisy and affected by low-level discontinuities in the lightcurve. There is tentative evidence of a possible rotational modulation at either 2.9, 3.1 or 6.3 days in the light curve, but the data does not enable us to estimate the period more precisely or to distinguish between these values.

4. Ground-based observations

4.1. Ground-based Photometric follow-up

Ground-based photometry was performed with the aim of refining the target ephemeris, to verify that none of its closest contaminant stars correspond to an eclipsing binary and to determine the contamination from nearby stars inside CoRoT’s photometric aperture mask (Deeg et al. 2009). CoRoT-15 was observed during a transit event on 2010 January 13 with time-series photometry at the IAC80 telescope, from HJD 2455209.480 to 2455209.676. The resultant lightcurve was not sufficiently precise to identify the expected transit on the target, due to photometric errors introduced by the presence of thin cirrus. However, the absence of large brightness variations in the neighboring stars allowed us to exclude nearby eclipsing binaries as a source of the signals that were observed by CoRoT. The contamination factor was derived from a measure of the distance and brightness of the nearby stars on a subset of these IAC80 R-filter images obtained with the best seeing of that night (1.7 arcsec). Ten nearby stars were identified, with six of them contaminating the CoRoT window aperture with a flux level that amounts to 1.9±0.3% of the main target flux. We checked furthermore that none of the known nearby stars is bright enough to be contaminating eclipsing binaries. The image of the sky around CoRoT-15 is shown in Fig. 2.

Fig. 2. The image of the sky around CoRoT-15 (star in the centre). Left: R-filter image with a resolution of 1.7” taken with the IAC80 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 positions of nearby stars which are in the Exo-Dat (Deleuil et al 2009) database.

4.2. Radial velocity follow-up

Radial velocity (RV) observations of CoRoT-15 were performed with the HARPS spectrograph (Mayor et al. 2003) based on the 3.6-m ESO telescope (Chile) as part of the ESO large program 184.C-0639 and with the HIRES spectrograph (Vogt et al. 1994) based on the 10-m Keck-1 telescope as part of NASA’s key science project to support the CoRoT mission.

HARPS was used with the observing mode obj_AB, without simultaneous thorium in order to monitor the Moon background light on the second fiber. The exposure time was set to 1 hour. A set of 9 spectra was recorded between November 24th 2009 and February 21th 2010. We reduced HARPS data and computed RVs with the pipeline based on the cross-correlation techniques (Baranne et al. 1996; Pepe et al. 2002). The signal-to-noise ratio (SNR) per pixel at 550 nm is in the range 3 to 7.8 for this faint target. It corresponds to the faint end in magnitude for HARPS follow-up observations. Radial velocities were obtained by weighted cross-correlation with a numerical G2 mask.

HIRES observations were performed with the red cross-disperser and the I2-cell to measure RVs. We used the 0.861” wide slit that leads to a resolving power of $R \approx 45,000$. The
Table 2. Radial velocity measurements of CoRoT-15 obtained by HARPS and HIRES. BJD is the Barycentric Julian Date.

| BJD       | RV±1σ [km s⁻¹] |
|-----------|----------------|
| -2 400 000 |                |
| HARPS 3.6-m ESO |
| 55159.81312 | 9.944 0.308    |
| 55169.77922 | 2.107 0.315    |
| 55235.60498 | 2.849 0.380    |
| 55236.59093 | 8.057 0.392    |
| 55241.55686 | 0.119 0.338    |
| 55243.55544 | -2.422 0.222   |
| 55246.56091 | -2.684 0.434   |
| 55247.53392 | -1.318 0.411   |
| 55248.53472 | 10.235 0.357   |
| HIRES 10-m Keck |
| 55221.76973 | 1.084 0.291    |
| 55221.81404 | 0.890 0.189    |
| 55221.82490 | 0.556 0.289    |
| 55221.89482 | -0.232 0.220   |
| 55221.90689 | -0.492 0.216   |
| 55221.97788 | -1.869 0.353   |
| 55221.99025 | -1.750 0.147   |
| 55222.98656 | -3.193 0.340   |
| 55222.99752 | -3.587 0.226   |
| 55223.73904 | 6.827 0.113    |
| 55224.82036 | 1.593 0.374    |
| 55224.83152 | 1.818 0.303    |
| 55225.04022 | -1.345 0.515   |

Fig. 3. Phase-folded radial velocity measurements of CoRoT-15 with HARPS (dark circle) and HIRES (open triangle)

4.3. spectral classification

Three HIRES spectra of CoRoT-15 were acquired without the iodine cell. Each spectrum was set in the barycentric rest frame, cleaned from cosmic rays and from the moon reflected light. The co-addition of these 3 spectra results in a master spectrum covering the wavelength range from 4100 Å to 7800 Å with a SNR per element of resolution in the continuum ranging from 20 at 5300 Å up to 70 at 6820 Å. The 9 co-added HARPS spectra unfortunately did not permit to reach a better SNR.

From the analysis of a set of isolated lines, we derived a \( \sin i \) of 19 ± 2 km s⁻¹. The spectroscopic analysis was carried out using the same methodology as for the previous CoRoT planets and described in details in Bruntt et al. (2010). However, the moderate SNR of the master spectrum of this faint target, combined to the marked rotational broadening of the spectral lines prevented an accurate measurement of the star’s photospheric parameters. The derived stellar parameters are reported in Table 3.

Following Santos et al. (2002) methodology, we also estimated the \( \sin i \) and an [Fe/H] index from the HARPS cross-correlation average parameters (FWHM and surface). Assuming a \( B-V \) of 0.5, we estimated the \( \sin i \) of the target to be 16±1 km s⁻¹ and [Fe/H] index close to zero (solar metallicity) in agreement with the spectral analysis.

5. System parameters

The time span of the CoRoT light curve is relatively short, and the RV data was collected on year later. Jointly analysing the two datasets therefore yields significantly improved constraints on the period \( P \) and time of transit centre \( T_0 \). To do this, we used a Metropolis-Hastings Markov Chain Monte Carlo (MCMC) algorithm (see appendix 1 of Tegmark et al. 2004 for a general description of MCMC algorithms and Winn et al. 2008 and references therein for a detailed description of their application to transits). This has the added advantage of yielding full posterior probability distributions for the fitted parameters, ensuring that the effects the well known degeneracy between the orbital inclination \( i \) and system scale \( a/R_s \) (which leads to highly skewed probability distributions for these parameters, as well as for the radius ratio \( R_c/R_s \)) are properly taken into account in the final uncertainties.
The light curve was first pre-processed to remove out-of-transit variability as follows. Outliers were identified using an iterative non-linear filter (see Aigrain et al. 2009), and a straight line was fitted to the region around each transit. The effect of contamination reported in section 4.1 was taken into account by subtracting a constant amount of flux equal to 1.9% of the mean flux from the light curve. Each section of the light curve was thus normalised, and a visual check was performed to ensure that no residual discontinuities affected the preprocessed light curve. The photometric uncertainties were then estimated from the out-of-transit scatter in the preprocessed light curve section around each transit. The light curve was modeled using the formalism of Mandel & Agol (2002). Given the relatively low SNR of the transits, we opted to fix the quadratic limb-darkening parameters \(K_u\) and \(K_d\) at the values given by Sing et al. (2010) for the star’s effective temperature, gravity and metallicity (adopted values: \(u_0 = 0.32, u_p = 0.30\)). The RV data were modelled using a Keplerian orbit with eccentricity fixed at zero, since the data show no evidence for a significant eccentricity. The relative zero-point of the HARPS and HIRES velocities, \(\delta V_0\), was allowed to vary freely. The parameters of the MCMC were thus \(P, T_0, R_\star/R_p, a/R_\star\), the radial velocity semi-amplitude \(K\), the systemic radial velocity \(V_\text{sys}\), and \(\delta V_0\).

After an initial chain of \(10^5\) steps to adjust the MCMC step sizes for each parameter, we ran 10 MCMC chains of \(10^5\) steps, each with different starting points. The convergence of the chains was checked using the Geldman-Rubin statistic (Geldman & Rubin 1992, Brooks & Geldman 1997). The chains were then combined (after discarding the first 10% of each chain, where the MCMC is settling from its starting point) to produce posterior probability distributions for each parameters. We report in Table 3 the median of the probability distribution for each parameter. To estimate uncertainties for each parameter, we computed the range of values which encloses 68.5% of the probability distribution (rejecting 16.25% at each extremum). Our uncertainties thus correspond to 68.5% confidence intervals, just as classical 1-\(\sigma\) uncertainties do for a Gaussian distribution. The best-fit transit model is shown superimposed on the folded light curve in Figure 4. To highlight the correlations between each parameter, we computed the posterior probability distributions and 2-D projections of the combined MCMC chain for these parameters in Figure 5.

We used the photospheric parameters from spectral analysis and the stellar density derived from the transit modeling to determine the star’s fundamental parameters in the \((T_{\text{eff}}, M_{\star}/R_{\star})\) space. Using STAREVOL evolution tracks (Palacios, private com.), we find the stellar mass to be \(M_\star = 1.32 \pm 0.10 M_\odot\) and the stellar radius \(R_\star = 1.46_{-0.10}^{+0.14} R_\odot\), with an age in the range 1.14–3.35 Gyr. This infers a surface gravity of \(\log g = 4.23_{-0.20}^{+0.12}\). The age, mass, and radius are in good agreement with the spectroscopic value.

Calculations using CESAM (Morel & Lebreton 2008) see also Guillot & Havel 2010 confirm these solutions. The age constraints, \(1.9\pm1.7\) Gyr, are however extremely weak, and yield possible pre-main sequence solutions with extremely young ages.

We derived for the transiting companion \(M_\star=63.3\pm4.1\ M_{\text{Jup}}\) and \(R_\star=1.12_{-0.15}^{+0.30}\ R_{\text{Jup}}\).
6. Discussion and Conclusion

CoRoT-15b is one of the rare transiting companions that lies in the theoretical mass domain of brown dwarfs (13-75 MJup, if one adopts the present IAU convention). Contrary to CoRoT-3b (Deleuil et al. 2008), that is located in the overlapping region between the massive planet and the brown-dwarf domain, CoRoT-15b is well in the mass domain of BDs. Expanding a bit the mass domain, one can easily include in this ensemble the whole mass “planets” (M ≥ 10 MJup) XO-3b (Johns-Krull et al. 2008) and WASP-18b (Hellier et al. 2009), and in the M-dwarf regime, OGLE-TR-122b (Pont et al. 2005b -123b (Pont et al. 2006) -106b (Pont et al. 2005b), and HAT-TR-205-013 (Bédat et al. 2007). Interestingly, all these objects are found to orbit F-type stars (see also Deleuil et al. 2008, with one exception; OGLE-TR-122b orbits a G-type dwarf but has a much longer orbital period (7.3 days compared to less than 4.3 days for all other objects).

Early- and mid-F-type dwarfs have the particularity of being fast rotators, independently of their age (Nordstrom et al. 1997), a consequence of a small or inessential outer convective zone, weak stellar winds, and reduced losses of angular momentum. The tides raised on a star by its close-in companion (planet, brown dwarf or star) have long been known to cause a threat to its survival (e.g. Pätzold & Rauer 2002). This is true when the star’s spin is slower than the orbital period of the companion, a common situation for close-in exoplanets. However, massive-enough companions have the possibility of spinning-up the star and may escape engulfment if the total angular momentum of the system is above a critical value (Levrard et al. 2009). Even in that case however, magnetic braking in the central star (e.g. see Barker & Ogilvie 2009) will lead to a loss of angular momentum that will be transferred to the orbit of the companion through tides and lead to orbital decay. We thus propose that close-in massive planets, brown dwarf or M-dwarf can survive when orbiting early or mid F-type dwarfs but that they tend to be engulfed by G-type (or late F-type) dwarfs. In the case of CoRoT-15, we thus expect that the star should be above ~ 1.25 M⊙ to avoid efficient spin-down, and that the system should be at or close to double-synchronisation (i.e. the spin period of the star should be close to the orbital period of its companion).

It is interesting to see that given the v sin i and stellar radius determinations, the projected spin period of the central star is P sin i = 3.9±1 days. An LS periodogram shows the presence of many peaks possibly due to low-level discontinuities in the lightcurve. The most robust peak compatible with the v sin i determination lies between 0.32 and 0.34 cycles/day, and may thus be linked to a stellar spin period between 2.9 and 3.1 days. The CoRoT-15 system thus appears to be indeed close to double-synchronous. Further observations of the system and in particular a precise determination of the stellar spin period would be a powerful mean of understanding the dynamical evolution of this system. Coupled to studies of similar systems, this may also yield strong constraints on the on the tidal dissipation factor in F-type dwarfs.

CoRoT-15b is also extremely interesting for its size in comparison with other objects in this mass range, and of evolution tracks for hydrogen-helium brown dwarfs and stars. Figure 6 shows that it appears inflated compared to standard evolution tracks for these kind of objects (Baraffe et al. 2003), although it may be compatible with a young age if the true size is at the lower-end of the one inferred from our measurements. However, we notice that the same problem arises for OGLE-TR-123b,
The two other known brown dwarfs with direct radius measurements, discovered in the 2MASS J05352184-0546085 eclipsing binary system (Stassun et al. 2006), have very large radii (5.0 and 6.5 R_Jup) but related to the very young age of the system (~1 Myr), still in the earliest stages of gravitational contraction.

In order to examine possible solutions to this puzzle (other than a systematic overestimation of the inferred sizes for the systems known thus far), we calibrate evolution tracks using CEPAM (Guillot & Morel 1995), but adding the dominant thermonuclear reaction cycle, namely the pp-chain (see Burrows & Chabrier, 2001). This results in a Return Grant. SA & NG acknowledge support from STFC standard grand by grant ESP2007-16480-C02-01 for their contribution to the success of the HARPS project and operation. HRES data presented herein were obtained at the W.M. Keck Observatory from telescope time allocated to the NASA through the agency's scientific partnership with the California Institute of Technology and the University of California. The French team wish to thank the Programme National de Planétologie (PNP) of CNRS/INSU and the French National Research Agency (ANR-08-ICJC-0102-01) for their continuous support to our planet search program. The team at IAC acknowledges support by grant ESP2007-64800-C02-02 of the Spanish Ministerio de Ciencia e Innovación. The German CoRoT Team (TLS and the University of Cologne) acknowledges DLR grants 500W0204, 500W0603, and 50QF07011. MG acknowledges support from the Belgian Science Policy Office in the form of a Return Grant. SA & NG acknowledge support from STFC standard grand ST/G002266. FB acknowledges the continuous support of PLS-230371.

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3 The recent discovery of the transiting brown dwarf LHS6343C by Johnson et al. (2010) also points to an inflated companion.
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