

# Transiting exoplanets from the CoRoT space mission XII. CoRoT-11b: a transiting massive “hot-Jupiter” in a prograde orbit around a rapidly rotating F-type star\*

D. Gandolfi<sup>1,2</sup>, G. Hébrard<sup>3</sup>, R. Alonso<sup>4</sup>, M. Deleuil<sup>5</sup>, E.W. Guenther<sup>1</sup>, M. Fridlund<sup>2</sup>, M. Endl<sup>6</sup>,  
P. Eigmüller<sup>1</sup>, Sz. Csizmadia<sup>7</sup>, M. Havel<sup>8</sup>, S. Aigrain<sup>9</sup>, M. Auvergne<sup>10</sup>, A. Baglin<sup>10</sup>, P. Barge<sup>5</sup>,  
A. S. Bonomo<sup>5</sup>, P. Bordé<sup>11</sup>, F. Bouchy<sup>3,12</sup>, H. Bruntt<sup>10</sup>, J. Cabrera<sup>7,13</sup>, S. Carpano<sup>2</sup>, L. Carone<sup>14</sup>,  
W. D. Cochran<sup>6</sup>, H. J. Deeg<sup>15</sup>, R. Dvorak<sup>16</sup>, J. Eisloffel<sup>1</sup>, A. Erikson<sup>7</sup>, S. Ferraz-Mello<sup>17</sup>, J.-C. Gazzano<sup>5,8</sup>,  
N. Gibson<sup>9</sup>, M. Gillon<sup>4,18</sup>, P. Gondoin<sup>2</sup>, T. Guillot<sup>8</sup>, M. Hartmann<sup>1</sup>, A. Hatzes<sup>1</sup>, L. Jorda<sup>5</sup>, P. Kabath<sup>7,19</sup>,  
A. Léger<sup>11</sup>, A. Llebaria<sup>5</sup>, H. Lammer<sup>20</sup>, P. J. MacQueen<sup>6</sup>, M. Mayor<sup>4</sup>, T. Mazeh<sup>21</sup>, C. Moutou<sup>5</sup>,  
M. Ollivier<sup>11</sup>, M. Pätzold<sup>14</sup>, F. Pepe<sup>4</sup>, D. Queloz<sup>4</sup>, H. Rauer<sup>7,22</sup>, D. Rouan<sup>10</sup>, B. Samuel<sup>11</sup>, J. Schneider<sup>13</sup>,  
B. Stecklum<sup>1</sup>, B. Tingley<sup>15</sup>, S. Udry<sup>4</sup>, and G. Wuchterl<sup>1</sup>

(Affiliations can be found after the references)

Received ; accepted

## ABSTRACT

The *CoRoT* exoplanet science team announces the discovery of CoRoT-11b, a fairly massive hot-Jupiter transiting a F6 V star ( $M_* = 1.27 \pm 0.05 M_\odot$ ,  $R_* = 1.37 \pm 0.03 R_\odot$ ,  $T_{\text{eff}} = 6440 \pm 120$  K), with an orbital period of  $P = 2.994329 \pm 0.000011$  days and semi-major axis  $a = 0.0436 \pm 0.005$  AU. The detection of part of the radial velocity anomaly caused by the Rossiter-McLaughlin effect shows that the transit-like events detected by *CoRoT* are due to a planet-sized transiting object in a prograde orbit. The relatively high projected rotational velocity of the star ( $v \sin i_* = 40 \pm 5$  km/s), places CoRoT-11 among the most rapidly rotating planet host stars discovered so far. With a planetary mass of  $M_p = 2.33 \pm 0.34 M_{\text{Jup}}$  and radius  $R_p = 1.43 \pm 0.03 R_{\text{Jup}}$ , the resulting mean density of CoRoT-11b ( $\rho_p = 0.99 \pm 0.15$  g/cm<sup>3</sup>) can be explained with a model for a hydrogen-planet with a solar composition and a high level of energy dissipation in its interior.

**Key words.** stars: planetary systems - techniques: photometry - techniques: radial velocities - techniques: spectroscopic

## 1. Introduction

Discovering and studying extrasolar planets, and in general planetary systems other than ours, aims at understanding whether the Solar System is “peculiar and unique” or “usual and unremarkable”. In this context, the discovery of a large population of Jupiter-like planets with a semi-major axis  $\lesssim 0.1$  AU (i.e., hot-Jupiters), as well as the detection of massive planets in very eccentric orbits (Moutou et al. 2009a; O’Toole et al. 2009) or even strongly misaligned with the stellar spin axis (Hébrard et al. 2008; Pont et al. 2009), has proven how the properties of extrasolar planets can be surprisingly different from the ones observed in the Solar System.

From this point of view, studies of transiting extrasolar planets are cornerstones for understanding the nature of planets beyond the Solar System, since a wealth of precious information can be gained (Winn 2010). As a matter of fact, the peculiar geometry of transiting planets makes them very special targets for obtaining direct measurements of the planet-to-star radius (Seager & Mallén-Ornelas 2003).

By combining time-series photometric observations acquired during the transit with radial velocity (RV) measurements of the host star, it is possible to derive the radius and mass of the planet, and hence its mean density, once the mass and radius of the star has been determined. Transits offer also a unique opportunity to measure the sky-projected angle ( $\lambda$ ) between the orbital angular momentum vector and the spin axis of the star (Gaudi & Winn 2007). This can be done by detecting the Rossiter-McLaughlin (RM) effect, i.e., the spectral distortion observed in the line profile of a rotating star as a second object passes in front of the stellar disk.

Furthermore transit surveys have the potential to enlarge the parameter space of planet host stars by detecting planets around stars usually not observed in radial velocity surveys. As it is well known, Doppler surveys typically focus on slowly rotating solar-like stars because high RV precision can easily be achieved. They usually discard more massive main sequence stars for which accurate RV measurements are rendered unfeasible by the rapid stellar rotation rate and the paucity of spectral lines. As a matter of fact, a few RV searches have been conducted up to now around A- and F-type stars (e.g. Lagrange et al. 2009; Guenther et al. 2009). Transit detections are not affected by the stellar

\* The *CoRoT* space mission, launched on December 27<sup>th</sup> 2006, has been developed and is operated by CNES, with the contribution of Austria, Belgium, Brazil, ESA (RSSD and Science Programme), Germany and Spain.

rotation and can lead to the discovery of planets around rapidly rotating F-type stars.

Space missions like *CoRoT* (*Convection, Rotation, and planetary Transits*, Baglin et al. 2006; Auvergne et al. 2009) and *Kepler* (Borucki et al. 2010; Koch et al. 2010) are crucial to increase the number of planets with well-known orbital and physical parameters, and consequently improve the database necessary to investigate all the aspects of the exoplanets population, down to the Earth-like mass-regime. The recent discoveries announced by the *CoRoT* exoplanet science team fully demonstrate the capability of the mission to determine the radius and the mean density of the transiting extrasolar planets, from the “transition desert regime” between brown dwarfs and planets (Deleuil et al. 2008), across hot and temperate Jupiter-like objects (Barge et al. 2008; Alonso et al. 2008; Bouchy et al. 2008; Aigrain et al. 2008; Moutou et al. 2008; Rauer et al. 2009; Fridlund et al. 2010; Deeg et al. 2010), and down to the Earth-like radius regime (Léger et al. 2009; Queloz et al. 2009).

In the present paper the *CoRoT Exoplanet Science Team* announces its eleventh transiting planet, namely CoRoT-11b, a fairly massive Jupiter-like planet in a relatively short-period orbit (about 3 days) around a rapidly rotating F6 dwarf star. By combining the high-precision photometric data from *CoRoT* with RV measurements and high signal-to-noise spectroscopy from the ground, we fully characterised the planet’s orbit and derived the main physical parameters of the planet-star system. Thanks to time-series RV measurements acquired during the transit we observed part of the RM effect and confirmed the planetary transit event.

## 2. CoRoT observations, data reduction and analysis

### 2.1. Satellite observations

CoRoT-11b was discovered during the *CoRoT*’s second long run towards the Galactic centre direction, i.e., the *CoRoT LRC02* run.<sup>1</sup> The observations lasted 145 days, from April 15<sup>th</sup> to September 7<sup>th</sup>, 2008. The *LRC02* field is centered at  $\alpha \approx 18^h 42^m$  and  $\delta \approx 6^\circ 39'$  (J2000), between the *Ophiuchus* and the *Serpens Cauda* constellations. The planet was detected transiting the *CoRoT* star<sup>2</sup> with ID=0105833549. The main designations of the planet host star CoRoT-11, along with its equatorial coordinates and optical and near-infrared photometry, are reported in Table 1, as retrieved from the *ExoDat* database (Deleuil et al. 2009) and *2MASS* catalogue (Cutri et al. 2003).

The transiting planet was detected after 51 days of observations, in the so-called *CoRoT alarm-mode* (Quentin et al. 2006; Surace et al. 2008). This observing strategy consists in processing and analysing a first set of photometric data in order to single out planetary transits while the *CoRoT* run is still on-going. This enabled us to switch the time sampling of the light curve from

<sup>1</sup> The ‘*LR*’ prefix means that the field is a long-run field (typically 150 days of observations). The letter ‘*c*’ refers to the Galactic centre direction. The last two digits ‘*02*’ indicate that the observed field is the second *CoRoT* long-run towards the Galaxy centre.

<sup>2</sup> See Carpano et al. (2009) for a full description of the *CoRoT* target nomenclature.

**Table 1.** CoRoT, GSC2.3, USNO-A2, and 2MASS identifiers of the planet host star CoRoT-11. Equatorial coordinates, optical and near infrared photometry are from the *ExoDat* catalogue (Deleuil et al. 2009) and *2MASS* catalogue (Cutri et al. 2003).

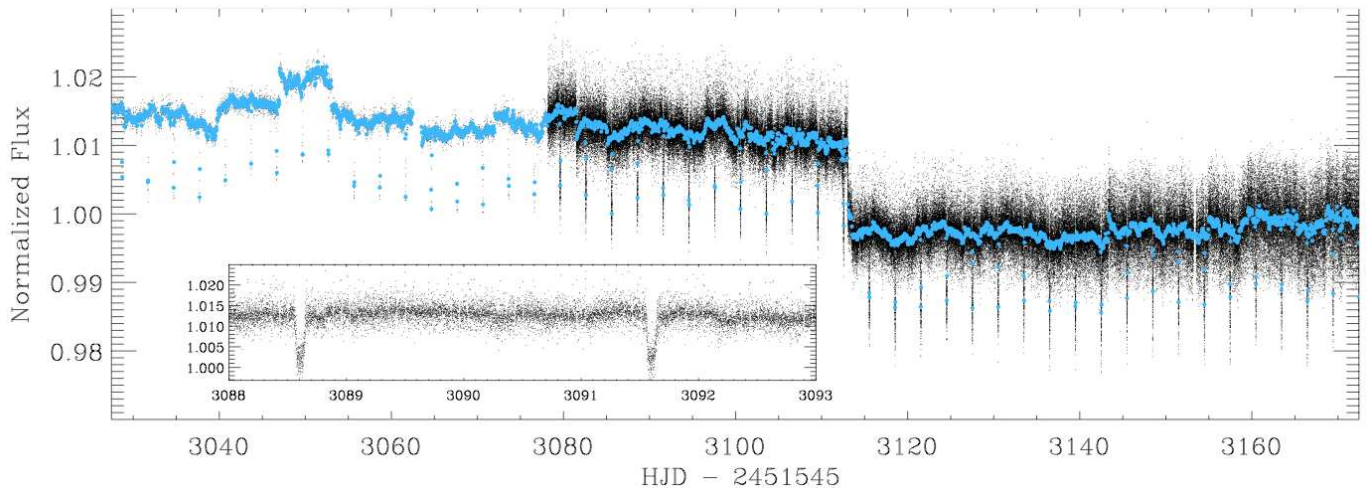
Main identifiers		
CoRoT ID	0105833549	
GSC2.3 ID	N1RO000587	
USNO-A2 ID	0900-13499974	
2MASS ID	18424494+0556156	
Coordinates		
RA (J2000)	18 <sup>h</sup> 42 <sup>m</sup> 44 <sup>s</sup> .95	
Dec (J2000)	05° 56′ 16″.12	
Magnitudes		
Filter	Mag	Error
B	13.596	0.024
V	12.939	0.019
<i>r</i> ′	12.638	0.019
<i>i</i> ′	12.283	0.053
J	11.589	0.021
H	11.416	0.029
Ks	11.248	0.022

512 to 32 seconds and trigger the ground-based follow-up observations (see Section 3). Thanks to an objective prism in the optical path of the *CoRoT* exoplanet channel (Auvergne et al. 2009), CoRoT-11 was observed in three broad-band colours (red, green, and blue), according to the specific photometric mask selected at the beginning of the run. This usually allows us to remove false positives mimicking planetary transit events, like stellar activity or eclipsing binaries. A total of 261 917 photometric data-points were collected for each colour channel, 8 349 of those were obtained with a time sampling of 512 sec, whereas 253 568 with 32 sec. The transit signal was detected in all the three color channels, with similar depth, and the same duration and ephemeris, as expected for a *bona-fide* planetary transit.

At the end of the *LRC02* observing run, the whole photometric data-set of CoRoT-11 was processed using the *CoRoT* reduction and calibration package described in Auvergne et al. (2009). The pipeline also flags bad photometric data-points collected during the entrance into and exit from the Earth’s shadow or strongly effected by hits of high-energy particles resulting from the crossing of the South Atlantic Anomaly (SAA).

### 2.2. CoRoT lightcurve and transit fit

In order to increase the signal-to-noise (S/N) ratio, the analysis of the photometric data was performed using the white light curve, as derived by adding together the signal from the three colour channels. CoRoT-11 has a close neighbour star at about 2″ northwest, falling well inside the *CoRoT* photometric aperture, as well as a handful of faint nearby stars spatially located around the *CoRoT* mask (see also Section 3.1 and Figure 3). According to the *ExoDat* database, the closest neighbour star is 2.1 magnitudes fainter than CoRoT-11 in the *r*′-band. Following



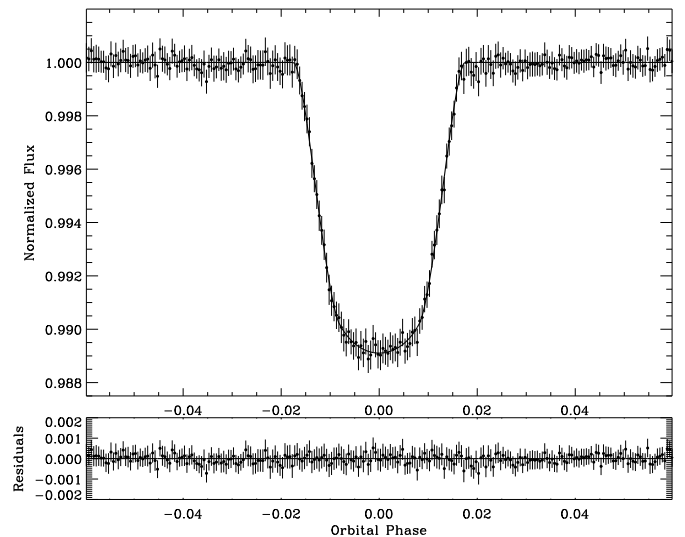
**Fig. 1.** The whole (145 days) cleaned light-curve of CoRoT-11, sampled at 512 seconds from the first  $\sim 50$  days, and at 32 seconds until the end of the run. For the sake of clarity, the blue dots represent 1-hour binned points. The inset plot is a zoom of the light curve showing two transits of CoRoT-11b. The light-curve has been arbitrarily normalised to the median value of the flux.

the method described in previous *CoRoT* papers (e.g., Alonso et al. 2008), we estimated that it contributes to about 12.2 % of the total flux of the photometric mask of CoRoT-11. Taking into account also the light coming from the fainter neighbours, the total contamination fraction rises up to  $13.0 \pm 1.5$  %. This fraction was removed from the whole data-set prior to analysing the white light curve.

A first “cleaning” of the raw *CoRoT* data was performed applying an iterative sigma-clipping algorithm. Most of the photometric points rejected according to this criterion (about 7.8 %), resulted from the crossing of the SAA and matched the photometric data previously flagged as outlier by the *CoRoT* automatic pipeline (Auvergne et al. 2009). The cleaned white light curve is plotted in Figure 1. It shows 49 transits with a depth of  $\sim 1$  %, occurring every  $\sim 3$  days. The transits are clearly visible, as shown in the inset of Figure 1. Out of 49 transits, 17 were detected with a 512 seconds time sampling, whereas 32 were observed with the oversampled rate (32 seconds).

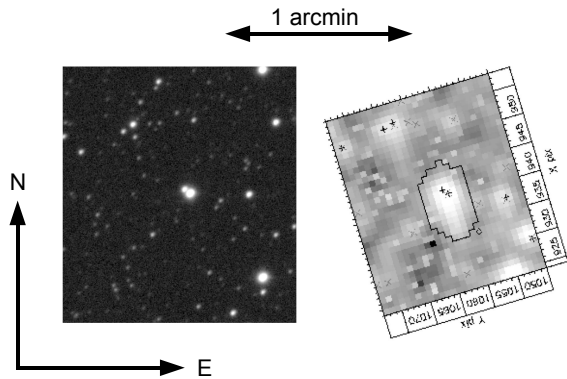
The *CoRoT* light curves are affected by a modulation of the satellite orbital period, which changes its shape and amplitude during a long run observation. Following the prescription of Alonso et al. (2008), the orbital signal of each  $j^{\text{th}}$  orbit was corrected using the signals from the previous and the following 30 orbits. The data points acquired during the transits were not considered in the estimation of the mean orbital signal of the  $j^{\text{th}}$  orbit.

In order to determine the period  $P$  and transit epoch  $T_{\text{tr}}$ , we first used an approximate ephemeris to build a phase-folded curve of the transit. A simple trapezoidal model was fitted to this curve to get the parameters of the average transit, i.e., depth, duration, centre and ingress/egress time. This model was then fitted to each individual transit, leaving only the centre as free parameter. A linear fit to the final observed-calculated ( $O-C$ ) diagram of the transit centres served to refine the ephemeris, and we iterated the process until the fitted line had no significant slope. Once the orbital period and transit epoch were de-



**Fig. 2.** Binned and phase-folded curve of the transit of CoRoT-11b, with the best fit model over-plotted and the residuals of the fit. The standard deviation of the points outside transit is of 230 ppm (with a phase sampling of  $5 \times 10^{-4}$ , corresponding to about 129 seconds). The mean error bar of the bins is of 239 ppm, revealing an insignificant amount of red noise.

rived (Table 4), we constructed a combined phase-folded transit curve to this ephemeris by successively normalising each transit to the regions surrounding it. In this case, as the star is not very active (see Figure 1), we used simple line fits to the phases between  $[-0.06, -0.02]$ , and  $[0.02, 0.06]$ , using the ephemeris of Table 4, and applied this normalisation to the whole section from phases  $[-0.06, 0.06]$ . We used a Savitzky-Golay filter to recognize a few remaining outliers before binning in phase. Taking into account the photometry rejected according to the first sigma-clipping

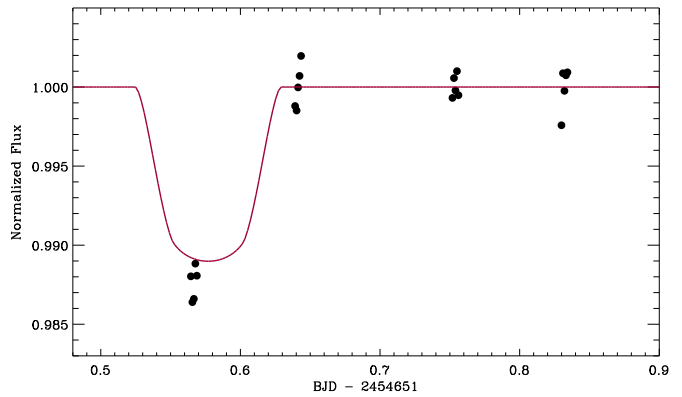


**Fig. 3.** Sky area around CoRoT-11. *Left*:  $r'$ -filter image as retrieved from the *ExoDat* database. CoRoT-11 is the brightest source in the centre of the image. The nearby contaminant star, about  $2''$  northwest from the main target, is clearly visible. *Right*: image acquired by *CoRoT*, at the same scale and orientation. The thick line around the target delimits the photometric mask used to integrate the signal of CoRoT-11. Note how the target and the contaminant are completely blurred and blended. The crosses on the image mark the position of the stars in the field.

algorithm, this process removed about 1.6 % of the remaining data points, leading to a final duty cycle of  $\sim 90$  %.

Finally, the data-points were binned in blocks of 0.0005 in phase, and the error bars were estimated as the standard deviation of the data points inside each bin divided by the square root of the number of points inside the bin. The phase-folded curve of the transit is shown in Figure 2.

The transit was fitted to a model using the formalism of Giménez (2006). To find the solution that best matches our data, we minimized the  $\chi^2$  using the algorithm AMOEBA (Press et al. 1992). The fitted parameters were the centre of the transit, the phase of start of the transit  $\theta_1$ , the planet to star radius ratio  $k = R_p/R_*$ , the orbital inclination  $i$  and the two non-linear limb darkening coefficients  $u_+ = u_a + u_b$  and  $u_- = u_a - u_b$ . We used a quadratic law for the limb darkening, given by  $I(\mu) = I(1)[1 - u_a(1 - \mu) - u_b(1 - \mu)^2]$ , where  $I$  is the distribution of brightness over the star and  $\mu$  is the cosine of the angle between the normal to the local stellar surface and the line of sight. The use of  $u_+$  and  $u_-$  is a better choice to avoid correlations between the two limb darkening coefficients  $u_a$  and  $u_b$ , as described in Giménez (2006). To estimate the errors in each of the parameters we performed the  $\chi^2$  minimization to five hundred different sets of data. These data-sets were constructed with different values for the contamination factor (estimated at  $13.0 \pm 1.5$  %), and different starting values to the AMOEBA minimization. To build each set, we: 1) subtracted the best solution to the data, 2) shifted circularly the residuals by a random quantity, to keep the low frequency content of the noise, and 3) added the subtracted solution in 1) to the new residuals. The errors were then estimated as the largest error among the standard deviations from the fitted parameters, or the  $\sigma$  of a fitted Gaussian distribution to the distribution of each of these parameters. The param-



**Fig. 4.**  $r$ -band light curve of CoRoT-11 as seen with the CCD camera mounted on the Swiss Leonard Euler 1.2m telescope at La Silla Observatory (Chile). The black circles mark each single exposure. The transit fit, as derived from the *CoRoT* light curve analysis is over-plotted.

eters and associated errors are listed in Table 4, along with the scaled semi-major axis  $a/R_*$ , as derived using equation 12 in Giménez (2006). Assuming a circular orbit (i.e.,  $e = 0$ ) and combining the scaled semi-major axis  $a/R_*$  with the orbital period  $P$  via the Kepler's laws, we derived the parameter  $M_*^{1/3}/R_* = 0.787 \pm 0.010$  in solar units, which leads to a mean stellar density  $\rho_* = 0.62 \pm 0.02$  g/cm $^3$ .

It is worth noticing that the standard deviation of the residuals outside the transit phase is 230 ppm, which is, within the uncertainties, identical to the mean error bar of each of the bins (239 ppm), thus revealing the small low frequency noise in the data after this analysis.

### 2.3. Planetary eclipse upper limits

We searched for the eclipse of the planet using the same techniques as described in Fridlund et al. (2010), and did not obtain any significant detection above 100 ppm in depth. Considering a circular orbit, we mapped the  $\chi^2$  levels of a fit to a trapezoid (with the shape parameters estimated from the transit) around the expected centre of the occultation. We can set an upper  $3\sigma$  limit for the planetary eclipse depth of 100 ppm, that we translated to an upper limit to the brightness temperature of 2650 K (Alonso et al. 2009).

## 3. Ground-based observations, data reduction and analysis

As already described in previous *CoRoT* discovery papers, intensive ground-based observations are mandatory to establish the planetary nature of the transiting candidates detected by *CoRoT*. These follow-ups are crucial to rule out possible false positives, i.e., physical configurations mimicking planetary transits, that cannot be excluded on the basis of meticulous light curve analyses only. Out of about 50 promising candidates detected per *CoRoT* long run field (see Carpano et al. 2009; Moutou et al. 2009b; Cabrera et al. 2009; Carone et al. 2010), usually only a handful turns out to be *bona fide* planetary objects. Furthermore, ground based observations are needed to as-

sess the planetary nature of the transiting object, derive the true mass of the planet, and measure the stellar parameters of the host star needed to accurately compute the planet radius<sup>3</sup>.

Follow-up campaigns of the planetary transit candidates detected by the Alarm Mode in the *LRc02* field started in the early Summer 2008. In the following subsection we will describe the complementary photometric and spectroscopic ground-based observations of CoRoT-11.

### 3.1. Photometric follow-ups

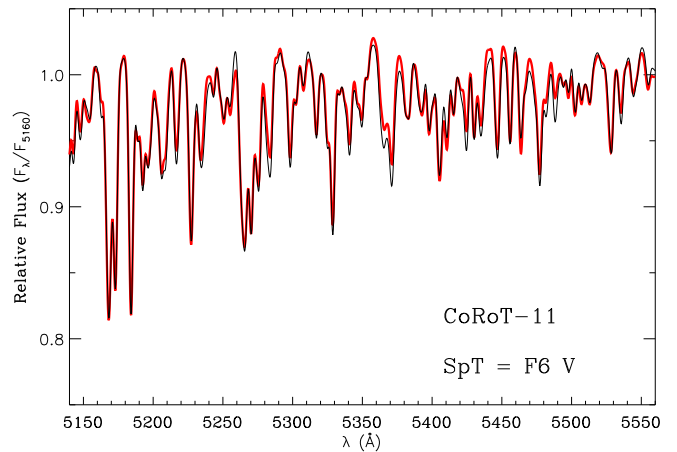
The objective prism placed along the optical path of the *CoRoT* exoplanet channel spreads the light of the observed targets over about 50 pixels on the CCDs, corresponding to a projected sky area of about  $20'' \times 10''$ . The total flux of each *CoRoT* target is then computed by integrating the pixel signal over a preselected photometric mask elongated along the dispersion direction and covering most of the point spread function (PSF). As already described in Section 2.2, this increases the possibility that the light of neighbour stars could contaminate the flux of the *CoRoT* target. Furthermore, what is believed to be a “good” planetary transit might actually turn out to be the eclipse of a faint nearby binary system whose light is diluted by the *CoRoT* target star.

As already mentioned above, CoRoT-11 has a close neighbour star that might be the potential source of false alarm (Figure 3). In order to exclude this scenario, we took advantage of the *CoRoT* ephemeris to perform the so called “on-off” photometry. In this procedure, candidates are photometrically observed with ground-based facilities at higher spatial resolution than *CoRoT*, during the transit (on-observation) and out of the transit (off-observation). The brightness of the candidates, as well as that of any nearby stars, is then monitored to unveil any potential background eclipsing binary. Full details of this method are described in Deeg et al. (2009).

According to this observing strategy, R-band photometry was carried out on July 4<sup>th</sup>, 2008, using the CCD camera mounted on the Swiss Leonard Euler 1.2 m telescope at La Silla Observatory (Chile), under photometric sky condition. Four sets of five consecutive exposures of 45 seconds each were acquired. The first set was obtained during the predicted transit (on-observation), whereas the remaining three were taken out of transit (off-observations). The data were reduced using standard IRAF routines<sup>4</sup>; aperture photometry was performed with the DAOPHOT package under the IRAF environment. Differential photometry was obtained for CoRoT-11, as well as for the nearby contaminants, using a set of nearby comparison stars. The on-off Euler observations clearly show that CoRoT-11 is the source of the transit events detected by *CoRoT* (Figure 4). The first photometric data-set shows a dimming of the light at the expected time and with roughly the same depth at mid-transit. No significant variations were detected in any of the nearby stars.

<sup>3</sup> We remind the reader that transits provide the direct measurement of “just” the planet-to-star radius ratio.

<sup>4</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), inc., under cooperative agreement with the National Science Foundation.



**Fig. 5.** Section of the TLS low-resolution spectrum of CoRoT-11 (thin black line). Overplotted with a thick lines is the best-fitting F6 V template. The spectra have been arbitrarily normalised to the flux at 5160 Å.

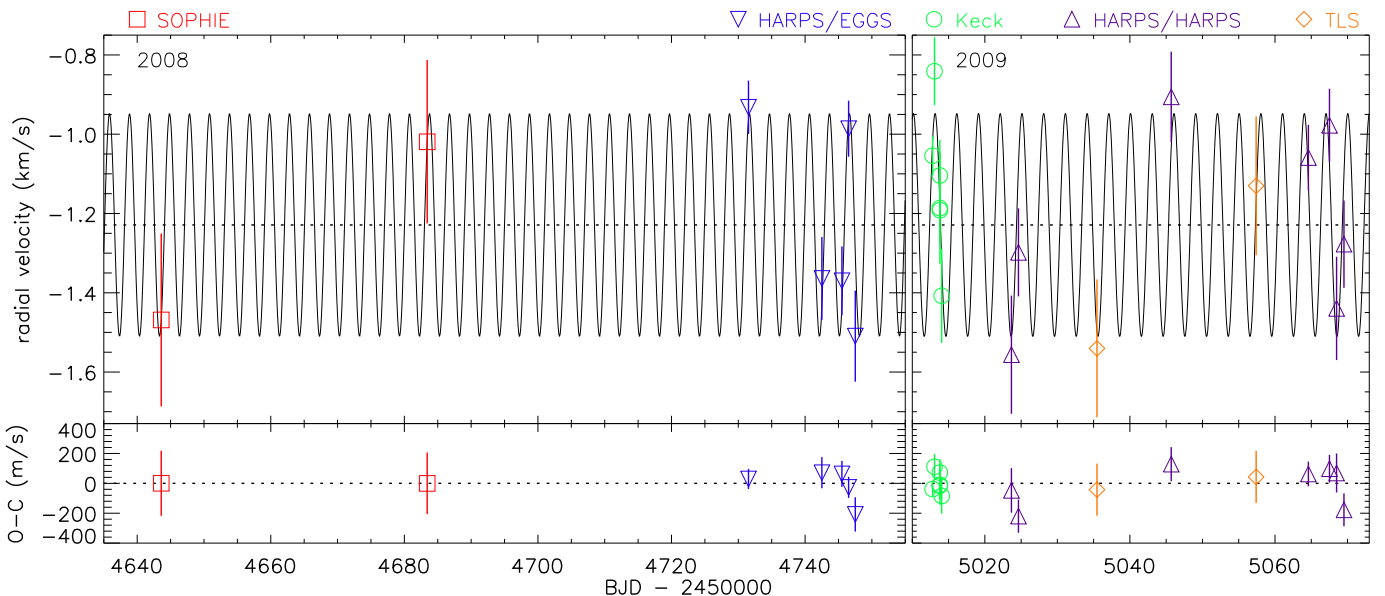
Further Johnson *R*-band photometric observations of CoRoT-11 were carried out using the 30 cm TEST telescope at the Thüringer Landessternwarte, Tautenburg (Germany), on September 7<sup>th</sup>, 2008. Full details of the instrument, observing strategy, and data reduction can be found in Eislöffel et al. (2007) and Eigmüller & Eislöffel (2009). Although these observations were performed at higher time-sampling than the ones at Euler, they were affected by poor weather conditions, especially in the second half of the night. Nevertheless, we succeeded to observe the transit ingress of CoRoT-11b at the expected *CoRoT* ephemeris and exclude significant photometric variations in the nearby contaminant stars.

### 3.2. Reconnaissance low-resolution spectroscopy

Low-resolution reconnaissance spectroscopy of the planet host star was performed with the long-slit spectrograph mounted at the Nasmyth focus of the 2 m Alfred Jensch telescope of the Thüringer Landessternwarte (TLS), Tautenburg, Germany. These observations were part of an intensive programme devoted to the spectroscopic “snapshot” of the planetary candidates detected by the Alarm Mode in the *LRc02* *CoRoT* field. They were useful to quickly classify the stars and derive a first estimation of their photospheric parameters. Furthermore, they allowed us to identify and remove giant stars, for which the transiting object would result in a low-mass stellar companion, as well as B-type objects and rapidly rotating early-type stars, for which high precision radial velocity measurements cannot be achieved.

CoRoT-11 was observed on August 8<sup>th</sup>, 2008 under clear and stable weather conditions. Three consecutive exposures of 20 minutes each were acquired and subsequently combined to remove cosmic ray hits and improve the S/N ratio. The data reduction was performed with a semi-automatic pipeline developed under the IDL<sup>5</sup> environment. Relative flux calibration was performed observing

<sup>5</sup> IDL is distributed by ITT Visual Information Solutions, Boulder, Colorado.



**Fig. 6.** *Top:* Radial velocity measurements of CoRoT-11 with  $1\text{-}\sigma$  error bars as a function of time, and Keplerian fit to the data. The data are from SOPHIE (red squares), HARPS (blue downward triangles and purple upward triangles for EGGs and HARPS modes, respectively), Keck (green circles), and TLS (orange diamonds). The left and right panels show the two observational seasons, in 2008 and 2009. The systemic radial velocity of  $V_r = -1.229 \pm 0.041$  km/s, as derived from the HARPS/EGGS data-set only, is plotted with a dotted horizontal line. *Bottom:* Residuals of the fit.

two spectro-photometric standard stars. The final extracted and co-added spectrum covers the wavelength range 4950–7320 Å, with a resolving power  $R \approx 2100$  and an average  $S/N \approx 60$ . The spectral type and the luminosity class of CoRoT-11 was derived by fitting the observed spectrum with a grid of suitable template spectra, as described in Frasca et al. (2003) and Gandolfi et al. (2008) and shown in Figure 5. We found that CoRoT-11 is a F6 V star, with an accuracy of about  $\pm 1$  sub-class (Table 4).

### 3.3. Radial velocity observations

The RV follow-up of the host star CoRoT-11 was started in summer 2008 by acquiring two high-resolution spectra with the SOPHIE spectrograph (Bouchy et al. 2009) attached to the 1.93 m telescope of the Haute-Provence Observatory (France). The instrument was set in its high efficiency (HE), leading to a resolving power of  $R \approx 40\,000$ . These observations revealed a rapidly rotating star with relatively broad spectral lines, corresponding to a projected rotational velocity ( $v \sin i_*$ ) of  $\sim 40$  km/s. According to the *CoRoT* ephemeris, the SOPHIE spectra were secured around the extreme orbital phases (i.e., phase 0.25 and 0.75), and showed a RV variation of  $\sim 450$  m/s in phase with the *CoRoT* ephemeris. Since the F6 V spectral type of the host star translates into a stellar mass of about  $1.3 M_\odot$ , the measured RV variation is compatible with a  $\sim 2 M_{\text{Jup}}$  Jupiter planet. Twelve additional RV measurements were obtained in summer 2008 and 2009 using the HARPS spectrograph (Mayor et al. 2003) mounted at the 3.6 m ESO telescope on La Silla (Chile). The spectra were acquired at different orbital phases, under good weather conditions and without strong moon light contamination. The data were acquired setting the spectrograph both in

the EGGs and HARPS standard modes, yielding a resolving power of  $R \approx 70\,000$  and  $R \approx 115\,000$ , respectively.

The extraction of both the SOPHIE and HARPS spectra was performed using the respective pipelines. Following the techniques described by Baranne et al. (1996) and Pepe et al. (2002), the radial velocities were measured from a weighted cross-correlation of the spectra with a numerical mask. We used a standard G2 mask that includes more than 3500 lines. Cross-correlations with F0 and K5 masks gave similar results. One SOPHIE spectrum and three HARPS spectra were corrected for small moonlight contamination following the method described in Pollacco et al. (2008) and Hébrard et al. (2008) which use a reference background sky spectrum obtained through a second fiber spatially located near the target. This led to a radial velocity correction of  $700 \pm 80$  m/s and below  $450 \pm 50$  m/s for the SOPHIE and HARPS spectra, respectively.

Two complementary RV measurements were acquired using the echelle spectrograph mounted on the 2 m Alfred Jensch telescope of the Thüringer Landessternwarte (TLS), Tautenburg (Germany), in July and August 2009. For each observing night, two consecutive exposures of 30 minutes each were recorded to increase the  $S/N$  ratio and remove cosmic ray hits. The adopted instrument set-up yielded a spectral resolution of about  $R \approx 30\,000$ . The data were reduced using standard IRAF routines. The wavelength solution was improved acquiring ThAr spectra right before and after each stellar observation. After accounting for instrumental shifts using telluric lines, the radial velocities were measured cross-correlating the target spectra with a spectrum of the RV standard star HR 5777 observed with the same instrument set-up.

As part of NASA’s key science programme in support of the *CoRoT* mission, further RV measurements were obtained using the HIRES spectrograph (Vogt et al.

**Table 2.** Radial velocities of the planet host star CoRoT-11 obtained with the SOPHIE, HARPS (EGGS and standard HARPS mode), COUDÉ@TLS, and HIRES spectrographs. The systemic velocities for each instrument, as derived from the circular Keplerian fit to the data, are reported on the right of the listed spectrographs. The footnote indicates the RV measurements that have been corrected for moonlight contamination.

HJD (days)	RV (km/s)	$\sigma_{RV}$ (km/s)	Texp (sec)	S/N per resolution element at 5500 Å
SOPHIE - HE Mode			$V_r = -0.920 \pm 0.160$ km/s	
2454643.60252 <sup>a</sup>	-1.164	0.218	1402	42
2454683.42036	-0.714	0.206	1607	50
HARPS - EGGS Mode			$V_r = -1.229 \pm 0.041$ km/s	
2454731.52836	-0.932	0.067	2700	88
2454742.51115	-1.364	0.104	2700	54
2454745.51100	-1.370	0.087	2700	66
2454746.51455	-0.986	0.071	2700	81
2454747.51953	-1.509	0.115	1800	48
HARPS - Standard Mode			$V_r = -1.336 \pm 0.044$ km/s	
2455023.66206 <sup>a</sup>	-1.663	0.149	3600	34
2455024.63997 <sup>a</sup>	-1.405	0.111	3600	48
2455045.69605 <sup>a</sup>	-1.013	0.114	3600	52
2455064.60739	-1.166	0.083	3300	64
2455067.51277	-1.085	0.092	3300	59
2455068.49041	-1.547	0.130	3300	42
2455069.51299	-1.384	0.110	3300	48
COUDÉ@TLS			$V_r = -0.640 \pm 0.130$ km/s	
245035.46055	-0.951	0.174	2 × 1800	25
245057.40390	-0.541	0.175	2 × 1800	25
HIRES			$V_r = -0.207 \pm 0.040$ km/s	
2455012.80417	-0.033	0.050	1200	61
2455013.06216	0.181	0.086	1200	71
2455013.78975	-0.165	0.089	900	54
2455013.80073	-0.083	0.090	900	56
2455013.81181	-0.170	0.135	900	56
2455013.82275	0.173	0.111	900	57
2455013.83360	-0.012	0.142	900	57
2455013.84473	0.099	0.073	900	56
2455013.85572	0.037	0.119	900	56
2455013.86677	0.274	0.108	900	55
2455013.87785	0.240	0.078	900	55
2455013.88881	0.017	0.100	900	56
2455013.89978	0.089	0.080	900	56
2455013.91097	-0.263	0.086	900	54
2455014.05389	-0.386	0.119	900	58

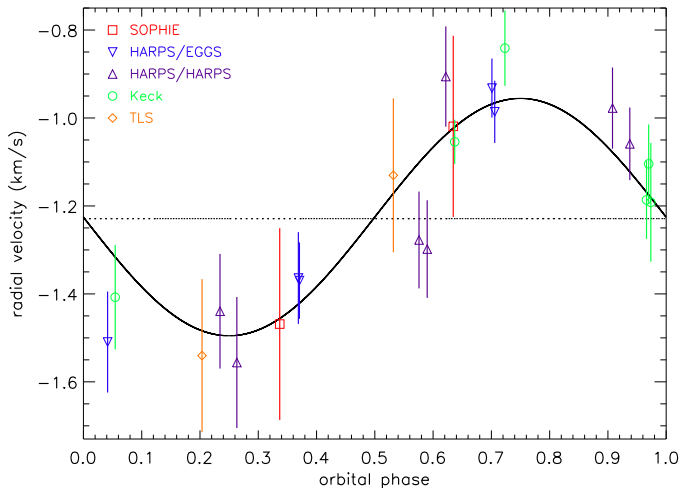
**Notes.**

<sup>(a)</sup> Corrected for moonlight contamination.

1994) mounted on the Keck I 10 m telescope, at the Keck Observatory (Mauna Kea, Hawai'i). With the aim of detecting the Rossiter-McLaughlin effect, 13 RV measurements were secured during the expected transit on July 1<sup>st</sup>, 2009 (UT). The observations were performed with the red cross-disperser and the  $I_2$  absorption cell to correct for instrumental shifts of the spectrograph. The 0''861 wide slit together with the 14'' tall decker was employed to allow proper background subtraction, yielding a resolving power of  $R \approx 50\,000$ . In order to adequately sample the RM anomaly, the exposure time was set to 900 seconds. Two extra spectra of 1200 seconds each were also acquired out

of transit, on June 30<sup>th</sup>, 2009 (UT). The spectra were reduced using IRAF standard routines. The HIRES RV measurements were derived using the iodine data modeling code “Austral” (Endl et al. 2000).

The final RV measurements of CoRoT-11 are reported in Table 2, along with error bars, exposure times, and S/N ratio. In spite of the good RV stability of the spectrographs used in the present work, the relatively high  $v \sin i_*$  of CoRoT-11 strongly affected the RV precision of our measurements, leading to an accuracy in the range  $\sim 100 - 200$  m/s, with a typical error bar of about 100 m/s even for the HARPS and HIRES data. The five data-sets,

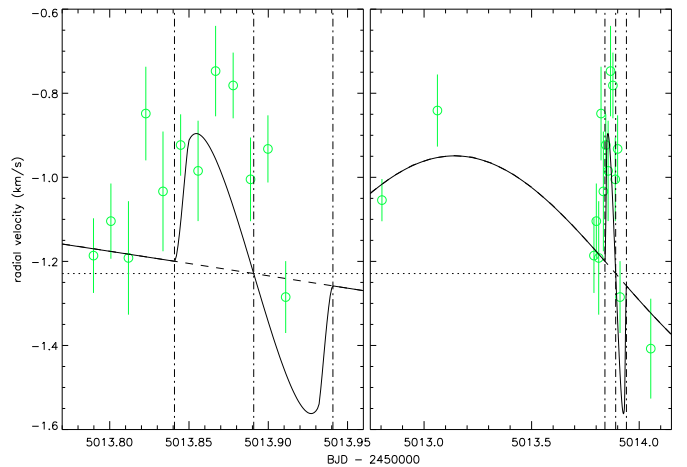


**Fig. 7.** Phase-folded radial velocity measurements of CoRoT-11 as a function of the orbital phase, and Keplerian fit to the data. The dashed-dotted horizontal line marks the systemic radial velocity  $V_r = -1.229 \pm 0.041$  km/s, as derived from the HARPS/EGGS data-set only.

i.e., the SOPHIE, HIRES, and TLS data, and the two HARPS modes, were simultaneously fitted with a Keplerian model, assuming a circular orbit. The HIRES RV measurements acquired during the transit were not used in the fit. Both period and transit central time were fixed according to the *CoRoT* ephemeris. A RV shift was let free to vary in the fit between the five data sets.

The RV measurements are plotted in Figure 6 together with the best fitting circular orbit. The derived orbital parameters are reported in Table 4, along with error bars which were computed from  $\chi^2$  variations and Monte Carlo experiments. The RV measurements led to a semi-amplitude  $K = 280 \pm 40$  m/s. The standard deviation of the residuals to the fit is  $\sigma_{O-C} = 88$  m/s, in agreement with the expected accuracy of the RV measurements. The reduced  $\chi^2$  is 1.1 for the 22 RV measurements used in the fit. The cross-correlation function bisectors show neither significant variations nor any trend as a function of both RV measurements and orbital phases. Thus the observed RV variations seem not to be caused by spectral line profile variations to any significant degree, but are mainly due to Doppler shifts. All the RV observations are consistent with the transit-signal detected from *CoRoT* being due to a hot-Jupiter sized planet orbiting the star.

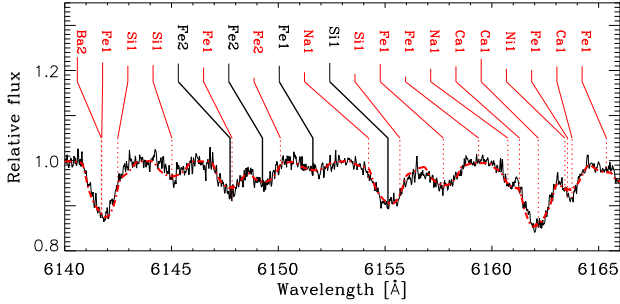
The phase-folded RV measurements are plotted in Figure 7. As already described, the orbit was assumed to be circular, which is a reasonable assumption for close-in hot-Jupiters. The radial velocities are not accurate enough to constrain the eccentricity with the orbital fit only. Indeed, a Keplerian fit with an eccentricity of about 0.6 provides a solution that agrees with the *CoRoT* ephemeris, with a RV semi-amplitude  $K$  which is 15 % larger than the one obtained for a circular orbit. The standard deviation of the residuals to this eccentric fit ( $\sigma_{O-C} = 95$  m/s) is marginally higher than the circular fit. Only extremely eccentric orbits with  $e > 0.7$  produce low-quality fits, with dispersions larger than 120 m/s. Nevertheless, we put some constraints on the possible value for the planet eccentricity taking advantage of the transit fit parameter  $M_*^{1/3}/R_*$ , from which



**Fig. 8.** Radial velocities of CoRoT-11 measured with Keck/HIRES around the transit that occurred on July 1<sup>st</sup>, 2010. The right panel shows all the data and the left panel shows a magnification on the transit. The dashed line shows the Keplerian fit without transit. The solid line shows the Rossiter-McLaughlin anomaly fit for  $\lambda = 0^\circ$ . The vertical lines show the transit first contact, mid-time, and fourth contact.

the mean stellar density can be inferred (Section 2.2). The obtained value of  $M_*^{1/3}/R_*$  depends on the eccentricity of the orbit. We found that for  $e \gtrsim 0.2$  the mean stellar density would result incompatible with a F6 dwarf star, being significantly higher than the expected value (Cox 2000).

The on-transit RV data of CoRoT-11 are plotted in Figure 8. Unfortunately, the HIRES observations were performed according to an old, slightly incorrect, transit ephemeris based on the analysis of the Alarm mode data only. Nevertheless, although the HIRES measurements cover only the first half of the transit, they clearly show that the Rossiter-McLaughlin (RM) anomaly has been detected, further confirming the occurrence of the transit events. The RM amplitude is large ( $\sim 400$  m/s), due to the fast stellar rotation. It further proves that the transiting object has a planetary size. The first part of the spectroscopic transit shows radial velocities that are blue-shifted by comparison with the Keplerian fit, which clearly indicates that the orbit is prograde. In addition, systematics seem to be present in the data at a level above the expected uncertainties for some measurements. It is thus difficult to constrain the spin-orbit angle with the current data. In Figure 8 we show a model with  $\lambda = 0^\circ$  and  $v \sin i_* = 40$  km/s, using the analytical approach developed by Ohta et al. (2005). The fit is not satisfying, suggesting in particular a  $v \sin i_*$  value larger than the one we derived from the SOPHIE RV data and the spectral analysis (Section 3.4), in order to have a larger amplitude for the anomaly. It is known that a discrepancy could be found between the  $v \sin i_*$  values measured from the RM effect and from the spectral modeling of line broadening, especially for fast rotators (see e.g., Simpson et al. 2010). Concerning the spin-orbit angle, the data are compatible with  $\lambda = 0^\circ$ . However, as for  $v \sin i_*$ , the moderate quality of the data-set prohibits accurate measurements. Additional RM observations of CoRoT-11 should be performed, with a full coverage of the event.



**Fig. 9.** A small section of the observed UVES spectrum (thin black line) together with the best fitting synthetic template (dashed line). The spectral lines used for the abundance analysis and the neighbouring lines are shown with black and red colours, respectively.

### 3.4. High-resolution spectroscopy and stellar analysis

To derive the fundamental atmospheric parameters of the planet host star, we observed CoRoT-11 with the high-resolution spectrograph UVES mounted at the 8.2m Very Large Telescope (ESO-VLT; Paranal Observatory, Chile). Two consecutive spectra of 2380 seconds each were acquired in service mode on the night 17/18 September, 2008, under the ESO program 081.C-0413(C). The star was observed through a  $0''.5$  wide slit, setting the UVES spectrograph to its Dic-1 mode (346+580). The adopted configuration yielded a resolving power of about 65 000, with a spectral coverage  $\lambda \approx 3000 - 6800 \text{ \AA}$ . The spectra were extracted and combined using standard IRAF packages, giving a final S/N ratio of about 160 at 5500  $\text{\AA}$ .

The effective temperature ( $T_{\text{eff}}$ ), surface gravity ( $\log g$ ), metallicity ( $[\text{Fe}/\text{H}]$ ), and projected rotational velocity ( $v \sin i_*$ ) of CoRoT-11 were derived following the procedure already adopted for other *CoRoT* host stars (e.g., Deleuil et al. 2008; Fridlund et al. 2010; Bruntt et al. 2010). We took advantage of different spectral analysis packages applied independently by different teams within the *CoRoT* community, e.g., the SME 2.1 (Valenti & Piskunov 1996; Valenti & Fischer 2005), the VWA (Bruntt et al. 2004, 2008, 2010) software. We found that the estimated values of the above mentioned physical parameters agree within the error bars. The final adopted values are  $T_{\text{eff}} = 6440 \pm 120 \text{ K}$ ,  $\log g = 4.22 \pm 0.23$ ,  $[\text{Fe}/\text{H}] = -0.03 \pm 0.08$ , and  $v \sin i_* = 40 \pm 5 \text{ km/s}$  (Table 4), with the latter value in perfect agreement with the one derived from the RV data (Section 3.3).

We also used the VWA software package to perform a detailed abundance analysis of the UVES spectrum of CoRoT-11, by iteratively fitting reasonably isolated spectral lines. Atmosphere models were interpolated in a grid of MARCS models (Gustafsson et al. 2008) and atomic data were extracted from VALD (Kupka et al. 1999). However, due to the relatively high  $v \sin i_*$  of the star, only 71 lines turned out to be sufficiently isolated and thus suitable for spectral analysis. A small section of the observed and fitted synthetic spectra is shown in Figure 9. Abundances were computed relative to the Sun to correct the oscillator strengths (see Bruntt et al. 2008; Bruntt 2009). We determine the atmospheric parameters by adjusting them

**Table 3.** Abundances relative to the Sun for five elements in CoRoT-11.

Element	$[A/H]$	$n$
Na I	$-0.10 \pm 0.15$	2
Si I	$0.10 \pm 0.09$	5
Si II	$0.19 \pm 0.18$	2
Ca I	$0.03 \pm 0.12$	4
Fe I	$-0.04 \pm 0.08$	44
Fe II	$-0.02 \pm 0.08$	6
Ni I	$-0.08 \pm 0.11$	8

to minimise the correlation of iron (Fe) with equivalent width (EW) and excitation potential (EP). Furthermore, we require that FeI and FeII have the same mean abundance within the uncertainty. To evaluate the uncertainty on the atmospheric parameters, we perturb them to determine when the correlations of FeI with EW or EP become significant or FeI and FeII abundances deviate by more than  $1\sigma$  (see Bruntt et al. 2008, for details). In Table 3 we list the abundances relative to the Sun for the five elements Na, Si, Ca, Fe, and Ni.

## 4. Results

### 4.1. Stellar parameters of the parent star CoRoT-11

To determine the mass and radius of the CoRoT-11 host star we took advantage of the stellar parameter ( $M_*^{1/3}/R_*$ ) as derived from the *CoRoT* light curve analysis (Section 2.2), and of the effective temperature and metallicity ( $T_{\text{eff}}$  and  $[\text{Fe}/\text{H}]$ ) as obtained from the spectral analysis (Section 3.4). We thus compare the location of the star on a  $\log(M_*^{1/3}/R_*)$  vs.  $\log(T_{\text{eff}})$  H-R diagram with evolutionary tracks computed with the CESAM code (Morel & Lebreton 2008). According to these theoretical models we obtained a stellar mass of  $M_* = 1.27 \pm 0.05 M_\odot$  and a stellar radius of  $R_* = 1.37 \pm 0.03 R_\odot$ , with an age of about  $2.0 \pm 1.0 \text{ Gyr}$  (Table 4). From these results we derived a surface gravity of  $\log g = 4.26 \pm 0.06$ , in good agreement with the spectroscopically determined value of  $\log g = 4.22 \pm 0.23$ . We also checked whether the high rotation rate of the star can account for a significant flattening at the poles. According to the equation by Claret (2000) and assuming that the star is seen almost edge-on, the equatorial and polar radii should differ by only  $\sim 0.6\%$ , making the flattening effect negligible.

We computed the interstellar extinction to the star following the general guidelines described in Gandolfi et al. (2008). The seven *BVr'i'JHKs* broad-band magnitudes, as retrieved from the *ExoDat* database, enabled us to construct the spectral energy distribution (SED) of CoRoT-11, covering a wide spectral range, from optical to near-infrared wavelengths (see Table 1). Using simultaneously all the photospheric colours encompassed by the SED, we derived the interstellar extinction to the star ( $A_V$ ) by fitting the observed SED with a theoretical one progressively reddened with an increasing value of  $A_V$ . The theoretical SEDs were computed using the *NextGen* stellar atmosphere model (Hauschildt et al. 1999) with the same  $T_{\text{eff}}$ ,  $\log g$ , and  $[\text{Fe}/\text{H}]$  as the star, the response curve of the *ExoDat* photometric system, and the extinction law by

Cardelli et al. (1989). Assuming a total-to-selective extinction  $R_V = A_V/E_{B-V} = 3.1$  (typical of the diffuse interstellar medium in our Galaxy), as well as a black body emission at the star's effective temperature and radius, we derived an extinction  $A_V = 0.55 \pm 0.10$  mag and a distance to the star  $d = 560 \pm 30$  pc (Table 4).

We attempted to derive the rotation period of the star from the *CoRoT* light curve. The Lomb-Scargle periodogram (Scargle 1982) applied to the out-of-transit data-points, shows only one significant broad peak at about  $8.5 \pm 2$  days, with a light curve amplitude of  $\sim 0.25$  %. This period is not compatible with the maximum rotation period of  $1.73 \pm 0.22$  days derived from the projected rotational velocity and radius of the planet host star. The detected signal at  $8.5 \pm 2$  days might be due to a 0.02 mag periodic variation of the nearby contaminant star located at about  $2''$  from CoRoT-11 (see Section 2.2 and 3.1). On the other hand, a low-level of magnetic activity of CoRoT-11 might account for no significant signals at  $\lesssim 2.0$  days, as confirmed from the absence of emission features in the core of the Ca II H & K and Balmer lines.

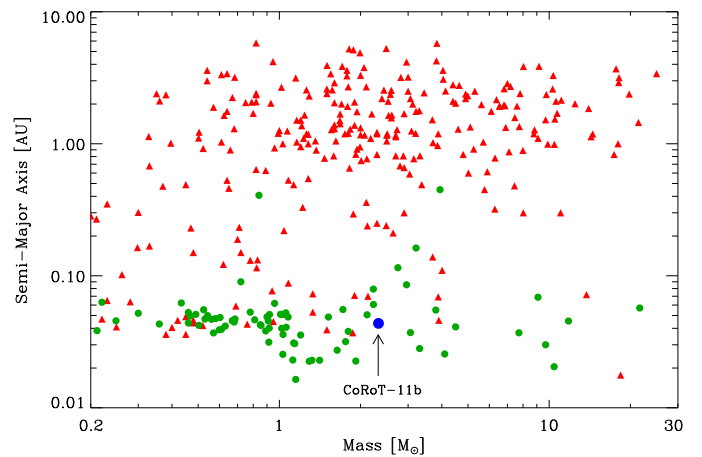
#### 4.2. Planetary parameters of CoRoT-11b

Based on the stellar mass and radius (Section 4.1), the RV curve semi-amplitude (Section 3.3), the planet-to-star radius ratio and the planet orbit inclination (Section 2.2), we derived a mass for CoRoT-11b of  $M_p = 2.33 \pm 0.34 M_{Jup}$  and a radius of  $R_p = 1.43 \pm 0.03 R_{Jup}$ , yielding a mean planetary density  $\rho_p = 0.99 \pm 0.15$  g/cm<sup>3</sup>. The planet orbits its host star at a distance of  $a = 0.0436 \pm 0.005$  AU in  $2.994339 \pm 0.000011$  days. The planetary mass has been obtained assuming an eccentricity  $e = 0$ . According to the results presented in Section 3.3, we cannot exclude a slightly eccentric orbit, with  $0 \lesssim e \lesssim 0.2$ . Nevertheless, for  $e = 0.2$  the planetary mass would decrease of about 4 %, i.e., well within the error bar of our estimation. A summary of the planetary parameters derived in the present work is reported in Table 4.

## 5. Discussion

Together with OGLE2-TR-L9b (Snellen et al. 2009) and WASP-33b (Collier Cameron et al. 2010) orbiting a F3 V ( $v \sin i_\star = 39$  km/s) and A5 V star ( $v \sin i_\star = 90 \pm 10$  km/s), respectively, CoRoT-11b is the third extrasolar planet discovered around a rapidly rotating main sequence star ( $v \sin i_\star = 40 \pm 5$  km/s). Furthermore, the planet host star CoRoT-11, with its effective temperature of  $T_{\text{eff}} = 6440 \pm 120$  K, is one of the hottest stars known to harbor an extrasolar planet.

Most of the bulk of known extrasolar planets have been detected with the RV method. Although this technique has dramatically increased the number of discoveries in the last fifteen years, it suffers from a strong selection bias, being mostly restricted to planets around slowly rotating stars ( $v \sin i_\star \lesssim 10$  km/s). This observational bias limits our knowledge of extra solar planets to mainly late-type solar-like stars. One of the big advantages of the transit method is that it is insensitive to the stellar rotation, enabling us to single out planets even around intermediate-mass stars (Collier Cameron et al. 2010). This allows us to enlarge the parameter space of planet host stars and gives us a chance



**Fig. 10.** Correlation diagram between mass and semi-major axis for extra solar planets detected in radial velocity (triangles) and transit surveys (circles). The position of CoRoT-11b is highlighted with an arrow.

to study the planet formation around A and F stars. Even if CoRoT-11b has been confirmed and studied thanks to a complementary and intensive RV campaign, it would have likely been rejected from any RV search sample due to the fast rotation of its parent star. As a matter of fact, about 20 RV measurements were needed to assess the planetary nature of CoRoT-11b and constrain its mass within  $\sim 15$  %. Anyway the RV signature of CoRoT-11b has been detected because of its high mass. Taking into account the accuracy of our RV measurements (100 – 200 m/s), if the mass of CoRoT-11b had been  $M_p \lesssim 0.5 M_{Jup}$ , it would have been not detected by the RV survey.

According to our planetary mass determinations ( $M_p = 2.33 \pm 0.34$ ), CoRoT-11b is among the most massive transiting hot-Jupiter discovered so far. It actually belongs to the poorly populated sub-group of objects with planetary masses around  $2 M_{Jup}$ . As already noticed by Torres et al. (2010), there seems to exist a lack of transiting hot-Jupiters with masses larger than about  $2 M_{Jup}$ . Based on the list of currently known transiting planets<sup>6</sup>, hot-Jupiters with masses in the range  $0.5 \lesssim M_p \lesssim 1.5 M_{Jup}$  seem to be  $\sim 5$  times more numerous than those with masses  $1.5 \lesssim M_p \lesssim 2.5 M_{Jup}$ . This trend is further confirmed from the number of planets discovered with the RV method. In Figure 10 the semi-major axis of the planets detected in radial velocity and transit surveys is plotted as a function of the planetary mass. Let us consider just the objects with  $a \lesssim 0.1$  AU and  $M_p \gtrsim 0.2 M_{Jup}$ , i.e., hot-Saturn and Jupiter planets. There is a clear clump of hot-giant planets with masses between the mass of Saturn ( $\sim 0.30 M_{Jup}$ ) and Jupiter, orbiting their parent star at about 0.04 – 0.06 AU. Starting from  $\sim 1.0 M_{Jup}$ , the number of hot-Jupiters seems to drop off, whereas the spread in the semi-major axis increases. For  $M_p \gtrsim 2 M_{Jup}$  the number of hot-Jupiters falls off significantly. The same trend is not seen for planets with  $1 \lesssim a \lesssim 5$  AU, although the lack of Saturn planets orbiting their parent at such a distance might be due to an obser-

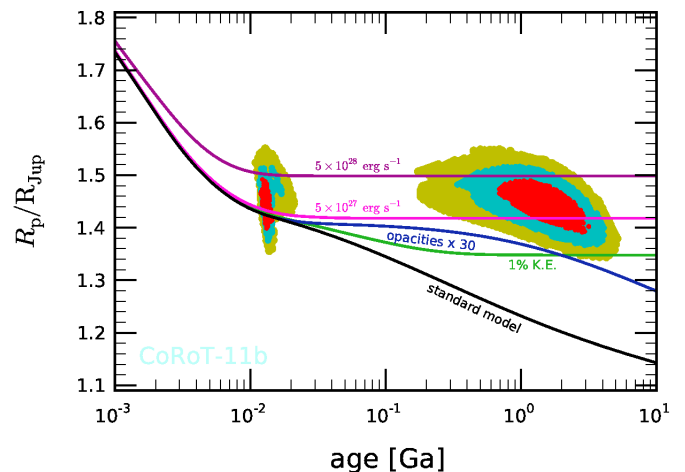
<sup>6</sup> We refer the reader to the Extra Solar Planets Encyclopedia for a constantly updated list of known extra solar planets (<http://exoplanet.eu/>).

vational bias of the RV technique. Nevertheless, since both the Doppler and transit methods are strongly sensitive in detecting close-in massive planets, we conclude that hot-Jupiters with  $M_p > 2 M_{\text{Jup}}$  are significantly less common than “normal” hot-Saturn and Jupiter planets.

By assuming that CoRoT-11b is a hydrogen-rich gas giant we estimated the planet’s thermal mass loss by applying the method outlined in detail in Lammer et al. (2009). Since the planet orbits a F6-type star with an age between 1.0 and 3.0 Gyr, we used the soft X-rays and EUV flux scaling law of Equation 12 of Lammer et al. (2009) and integrated the thermal mass loss during the planets history up to the two age values given above. By using the stellar and planetary parameters and a heating efficiency  $\eta$  for hydrogen-rich thermospheres, which can be considered between 10 - 25 % (Lammer et al. 2009; Murray-Clay et al. 2009), we obtained a present time mass loss rate for CoRoT-11b of about  $2.0 \times 10^{10}$  g/s or an integrated loss of 0.07 % of its present mass ( $\eta = 10$  %), and about  $5.0 \times 10^{10}$  g/s, or 0.18 % ( $\eta = 25$  %) if the host star and planet are 1.0 Gyr old. In case the star/planet system is 3.0 Gyr old we estimated a mass loss rate of about  $3.0 \times 10^9$  g/s, or 0.1 % ( $\eta = 10$  %) and about  $7.7 \times 10^9$  g/s, or 0.25 % ( $\eta = 25$  %) during the planet lifetime. These loss rates are in good agreement with hydrodynamic escape model results for typical hot Jupiters (Yelle et al. 2008). Although the planet radius is  $1.43 \pm 0.03 R_{\text{Jup}}$ , the main reason why the thermal mass loss of CoRoT-11b is not significant is related to the large mass of the planet of  $2.33 \pm 0.34 M_{\text{Jup}}$ . According to Lammer et al. (2009), only hot gas giant planets with  $\rho_p \ll 1 \text{ g/cm}^3$  should experience large thermal mass loss.

In order to investigate whether a standard model for an irradiated planet can account for the density of CoRoT-11b, we computed stellar and planetary evolution models using CESAM (Morel & Lebreton 2008) and CEPAM (Guillot & Morel 1995), as described in Bordé et al. (2010) and Guillot & Havel (2010). The results are shown in Figure 11 where the evolution of the size of CoRoT-11b is plotted as a function of the system age. The colours indicate distance in standard deviations from the inferred effective temperature and mean stellar density, i.e., less than  $1\sigma$  (red),  $2\sigma$  (blue) or  $3\sigma$  (green). These constraints are compared to planetary evolution models for a homogeneous solar-composition hydrogen-planet, with different hypotheses: (1) using a “standard model”, i.e., without additional sources of heat; (2) by increasing interior opacities by a factor 30; (3) by adding a fraction ( $\sim 1\%$ ) of the incoming stellar energy and dissipating it at the centre; (4) and (5) by dissipating  $5 \times 10^{27}$  and  $5 \times 10^{28}$  erg/s at the centre of the planet. The first three cases correspond to standard recipes used to explain the inflated giant exoplanets (Guillot 2008). The last two cases correspond to higher dissipation levels required to explain the planet size for the oldest ages.

Interestingly, as for CoRoT-2b (Guillot & Havel 2010), two classes of solutions are found: (i) the standard solution for which the host star is on the main sequence (with an age of about  $2.0 \pm 1.0$  Gyr) and the planet requires a high level of dissipation in its interior in order to account for its large size; (ii) a very young class of solutions in which the star is still on the pre-main sequence (PMS) phase (with an age of about  $12 \pm 2$  Myr) and the planet size can be quite naturally explained with a “standard model”. However, the latter scenario is in contradiction with the absence of the detectable  $\text{Li I } \lambda 6708 \text{ \AA}$  line in



**Fig. 11.** Evolution of the size of CoRoT-11b (in Jupiter units,  $1 R_{\text{Jup}} = 71\,492$  km) as a function of the age of the system (in Ga= $10^9$  years). The coloured areas correspond to constraints derived from stellar evolutionary models matching the mean stellar density and effective temperature within a certain number of standard deviations: less than  $1\sigma$  (red),  $2\sigma$  (blue) or  $3\sigma$  (green). The curves are evolutionary tracks for CoRoT-11b computed assuming a planetary mass of  $M = 2.33 M_{\text{Jup}}$  and equilibrium temperature  $T_{\text{eq}} = 1657$  K), and using different models as labelled (see text for more details).

the spectra of CoRoT-11. According to our effective temperature determination ( $T_{\text{eff}} = 6440 \pm 120$  K), CoRoT-11 would belong to the narrow class of F-stars which have suffered strong surface lithium depletion during the first billion years of their life. Indeed, studies of the lithium content in the photosphere of F-type stars in galactic clusters and field stars have revealed the presence of a narrow dip in the lithium abundance for effective temperature between 6500 and 6800 K (Mallik et al. 2003; Böhm-Vitense 2004). While the so called “lithium-dip” is absent in the Pleiades (Pilachowski et al. 1987) and in general in all the young cluster ( $\lesssim 100$  Myr), this dip is well observed in older cluster like the Hyades (700 Myr; Boesgaard & Tripicco 1986a), NGC 752 (1.7 Gyr; Hobbs & Pilachowski 1986), as well as in many field F-stars (e.g., Boesgaard & Tripicco 1986b).

We thus believe that an age of  $2.0 \pm 1.0$  Gyr is more plausible for the planet-star system. In any case, CoRoT-11b is another inflated planet hosted by a solar-like metallicity star, thereby strengthening the trend between stellar metallicity and quantity of heavy elements in the giant planets (Guillot 2008).

*Acknowledgements.* This paper is based on observations carried out at the European Southern Observatory (ESO), La Silla and Paranal (Chile), under observing programs numbers 081.C-0388, 081.C-0413, and 083.C-0186. The authors are grateful to the staff at ESO La Silla and ESO Paranal Observatories for their support and contribution to the success of the HARPS and UVES observing runs.

This paper is also based on observations performed with SOPHIE at the Observatoire de Haute-Provence, France, under observing program PNP.08A.MOUT.

Part of the data presented herein were obtained at the W.M. Keck Observatory from telescope time allocated to the National Aeronautics and Space Administration through the agency’s scientific partnership with the California Institute of Technology and the University of California. The Observatory was made possible by the

**Table 4.** CoRoT-11b - Planet and star parameters.

<i>Ephemeris</i>	
Planet orbital period $P$ [days]	$2.994330 \pm 0.000011$
Planetary transit epoch $T_{\text{tr}}$ [HJD-2 400 000]	$54597.6790 \pm 0.0003$
Planetary transit duration $d_{\text{tr}}$ [h]	$2.5009 \pm 0.0144$
<i>Results from radial velocity observations</i>	
Orbital eccentricity $e$	0 (fixed)
Radial velocity semi-amplitude $K$ [m/s]	$280.0 \pm 40.0$
O-C residuals [m/s]	88
<i>Fitted transit parameters</i>	
Planet-to-star radius ratio $k = R_p/R_*$	$0.1070 \pm 0.0005$
Linear limb darkening coefficient $u_+$	$0.61 \pm 0.06$
Linear limb darkening coefficient $u_-$	$0.02 \pm 0.04$
Orbital phase of planetary transit ingress ( $\theta_1$ )	$-0.0174 \pm 0.0001$
<i>Deduced transit parameters</i>	
Scaled semi-major axis $a/R_*$	$6.890 \pm 0.080$
$M_*^{1/3}/R_*$ [solar units]	$0.787 \pm 0.010$
Mean stellar density $\rho_*$ [ $\text{g}/\text{cm}^3$ ]	$0.69 \pm 0.02$
Inclination $i$ [deg]	$83.170 \pm 0.150$
Impact parameter <sup>a</sup> $b$	$0.818 \pm 0.008$
<i>Spectroscopic parameters</i>	
Effective temperature $T_{\text{eff}}$ [K]	$6440 \pm 120$
Surface gravity $\log g^b$ [dex]	$4.22 \pm 0.23$
Surface gravity $\log g^c$ [dex]	$4.26 \pm 0.06$
Metallicity [Fe/H] [dex]	$-0.03 \pm 0.08$
Stellar rotational velocity $v \sin i_*$ [km/s]	$40.0 \pm 5.0$
Spectral type	F6 V <sup>d</sup>
<i>Stellar physical parameters from combined analysis</i>	
Star mass $M_*$ [ $M_\odot$ ]	$1.27 \pm 0.05$
Star radius $R_*$ [ $R_\odot$ ]	$1.37 \pm 0.03$
Age of the star $t$ [Gyr]	$2.0 \pm 1.0$
Interstellar extinction $A_V$ [mag]	$0.55 \pm 0.10$
Distance of the system $d$ [pc]	$560 \pm 30$
<i>Planetary physical parameters from combined analysis</i>	
Planet mass $M_p$ [ $M_J$ ] <sup>e</sup>	$2.33 \pm 0.34$
Planet radius $R_p$ [ $R_J$ ] <sup>e</sup>	$1.43 \pm 0.03$
Planet density $\rho_p$ [ $\text{g}/\text{cm}^3$ ]	$0.99 \pm 0.15$
Orbital semi-major axis $a$ [AU]	$0.0436 \pm 0.005$
Equilibrium temperature <sup>f</sup> $T_{\text{eq}}$ [K]	$1657 \pm 55$

**Notes.**<sup>(a)</sup> The impact parameter is defined as  $b = \frac{a \cdot \cos i}{R_*}$ <sup>(b)</sup> Derived from the spectroscopic analysis.<sup>(c)</sup> Derived using the light curve parameter  $M_*^{1/3}/R_*$  and the stellar mass as inferred from stellar evolutionary models.<sup>(d)</sup> With an accuracy of  $\pm 1$  sub-class.<sup>(e)</sup> Radius and mass of Jupiter taken as 71492 km and  $1.8986 \times 10^{30}$  g, respectively.<sup>(f)</sup> Zero albedo equilibrium temperature for an isotropic planetary emission.

generous financial support of the W.M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

The team at IAC acknowledges support by grant ESP2007-65480-C02-02 of the Spanish Ministerio de Ciencia e Innovacion. The

German *CoRoT* Team (TLS and the University of Cologne) acknowledges DLR grants 50OW0204, 50OW0603, and 50QP07011.

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

## References

- Aigrain, S., Pont, F., Fressin, F., et al. 2009, *A&A*, 506, 425
- Alonso, R., Auvergne, M., Baglin, A., et al. 2008, *A&A*, 482, L21
- Alonso, R., Alapini, A., Aigrain, S. et al. 2009, *A&A*, 506, 353
- Anderson, D.R., Hellier, C., Gillon, M., et al. 2010, *ApJ* 709, 159
- Auvergne, M., Bodin, P., Boissard, L., et al. 2009, *A&A*, 506, 411
- Baglin, A., Auvergne, M., Boissard, L., et al. 2006, 36th COSPAR Scientific Assembly, 36, 3749
- Böhm-Vitense E. 2004, *AJ*, 128, 2435
- Baranne, A., Queloz, D., Mayor, M., et al. 1994, *A&AS*, 119, 373
- Barge, P., Baglin, A., Auvergne, M., et al. 2008, *A&A*, 482, L17
- Boesgaard, A. M. & Tripicco, M. J. 1986, *ApJ*, 302, 49
- Boesgaard, A. M. & Tripicco, M. J. 1986, *ApJ*, 303, 724
- Bordé P., Bouchy F., Deleuil M., et al. 2010, *A&A*, submitted
- Borucki, W. J., et al. 2010, *ApJ*, 713, L126
- Bouchy, F., Queloz, D., Deleuil, M., et al. 2008, *A&A*, 482, L25
- Bouchy, F., Hébrard, G., Udry, S., et al. 2009, *A&A*, 505, 853
- Bruntt, H., Bikmaev, I.F., Catala, C., et al. 2004, *A&A*, 425, 683
- Bruntt, H., De Cat, P. & Aerts, C. 2008, *A&A*, 478, 487
- Bruntt, H. 2009, *A&A*, 506, 235
- Bruntt, H., Deleuil, M., Fridlund M. et al. 2010, eprint arXiv:1005.3208
- Cabrera, J., Fridlund, M., Ollivier, M., et al. 2009, *A&A* 506, 501
- Collier Cameron, A., Günther, E., Smalley, B., et al. 2010, eprint arXiv:1004.4551
- Carpano, S., Cabrera, J., Alonso, R., et al. 2009, *A&A* 506, 491
- Cardelli J.A., Clayton G.C. & Mathis J.S. 1989, *ApJ* 345, 245
- Carone, L., Gandolfi, D. et al., *A&ASubmitted*
- Claret, A. 2000, *A&A*, 359, 289
- Cox, A.N. 2000, "Allen's astrophysical quantities", 4<sup>th</sup> ed., edited by A.N. Cox, AIP Press
- Cresswell, P., Dirksen, G., Kley, W. nad Nelson, R.P. 2007, *A&A* 473, 329
- Cutri R.M., Skrutskie M.F., van Dyk S. et al. 2003, *2MASS All-Sky Catalog of Point Sources*, NASA/IPAC Infrared Science Archive
- Deeg, H. J., Gillon, M., Shporer, A., et al. 2009, *A&A*, 506, 343
- Deeg, H. J., Moutou, C., Erikson, 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
- Eigmüller, P. & Eislöffel, J. 2009, *Transiting Planets, Proceedings of the International Astronomical Union, IAU Symposium "Transiting Planet"*, 253, 340
- Eislöffel, J., Hatzes, A. P., Rauer, H., et al. 2007, *Solar and Stellar Physics Through Eclipses ASP Conference Series*, 370, 91
- Endl, M., Kürster, M., Els, S. 2000, *A&A*, 362, 585
- Frasca A., Alcalá J.M., Covino E. et al. 2003, *A&A* 405, 149
- Fridlund, M., Hébrard, G., Alonso, R., et al. 2010, *A&A*, 512, A14
- Gandolfi, D., Alcalá, J.M., Leccia, S., et al. 2008, *ApJ*, 686, 1303
- Gaudi, B. S. & Winn J. N 2007, *ApJ*, 655, 550
- Guenther, E. W., Hartmann, M., Esposito, M., et al. 2009, *A&A*, 507, 1659
- Guillot, T. & Morel, P. 1995, *A&AS*, 109, 109
- Guillot, T. 2008, *Physica Scripta*, 130, 014023
- Guillot, T. & Havel, M. 2010, *A&A*, submitted
- Giménez, A. 2006, *A&A*, 450, 1231
- Gustafsson, B., Edvardsson, B., Eriksson, K., et al. 2008, *A&A*, 486, 951
- Hauschildt P.H., Allard F. & Baron E. 1999, *ApJ* 512, 377
- Hébrard, G., Bouchy, F., Pont, F., et al. 2008, *A&A*, 481, 52
- Hobbs, L. M. & Pilachowski, C. 1986, *ApJ*, 309, 17
- Kallrath, J. & Milone, E.F. 2009, "Eclipsing Binary Stars: Modeling and Analysis", Springer-Verlag New York
- Koch, D., et al. 2010, *ApJ*, 713, L79
- Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C., Weiss, W. W., 1999, *A&AS*, 138, 119
- Lammer, H., Odert, P., Leitzinger, M. et al. 2009, *A&A*, 506, 399
- Lagrange, A.-M., Desort, M., Galland, F., et al. 2009, *A&A*, 495, 335
- Léger, A., Rouan, D., Schneider, J., et al. 2009, *A&A*, 506, 287
- Lubow, S.H. & Ogilvie, G.I. 2001, *ApJ* 560, 997
- Mayor, M., Queloz, D. 1995, *Nature*, 378, 355
- Mayor, M., Pepe, F., Queloz, D., et al. 2003, *Msngr.*, 114, 20
- Mallik, Sushma V., Parthasarathy, M. & Pati, A. K. 2003, *A&A*, 409, 251M
- Morel, P. & Lebreton, Y. 2008, *Ap&SS*, 316, 61
- Moutou, C., Bruntt, H., Guillot, T., et al. 2008, *A&A*, 488, L47
- Moutou, C., Hébrard, G., Bouchy, F., et al. 2009, *A&A*, 498, L5
- Moutou, C., Pont, F., Bouchy, F., et al. 2009, *A&A*, 506, 321
- Murray-Clay, R. A., Chiang, E. I., & Murray, N. 2009, *ApJ*, 693, 23
- O'Toole, S. J., Tinney, C. G., Jones, H. R. A., et al. 2009, *MNRAS*, 392, 641
- Ohta, Y., Taruya, A., and Suto, Y. 2005, *ApJ*, 622, 1118
- Papaloizou, J.C.B. & Terquem, C. 2006, *Reports on Progress in Physics*, 69, 119
- Pepe, F., Mayor, M., Galland, F., et al. 2002, *A&A*, 388, 632
- Pilachowski, C. A., Booth, J. & Hobbs, L. M. 1987, *PASP*, 99, 1288
- Pollacco, D., Skillen, I., Collier Cameron, A., et al. 2007, *MNRAS*, 385, 1576
- Pont, F., Endl, M., Cochran, W. D., et al., 2009, *MNRAS*, 402, 1
- Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P. 1992, "Numerical recipes in C. The art of scientific computing", Cambridge: University Press, 2<sup>nd</sup> edition
- Queloz, D., Bouchy, F., Moutou, C., et al. 2009, *A&A*, 506, 303
- Quentin, C.G., Barge, P., Cautain, R., et al. 2006, in *ESA Special Publication*, 1306, 409
- Rauer, H., Queloz, D., Csizmadia, S., et al. 2009, *A&A*, 506, 281
- Scargle, J. D. 1982, *ApJ*, 263, 835
- Seager, S., Mallén-Ornelas, G. 2003, *ApJ*, 585, 1038
- Simpson, E. K., Pollacco, D., Hébrard, G., et al. 2010, *MNRAS*, in press [arXiv:0912.3643]
- Snellen, I. A. G., Koppenhoefer, J., van der Burg, R. F. J., et al. 2009, *A&A*, 497, 545
- Surace, C., Alonso, R., Barge, P., et al. 2008, *SPIE*, 7019, 111
- Torres, G., Bakos, G.Á., Hartman, J. et al. 2010, *ApJ*, 715, 458
- Valenti, J. A. & Piskunov, N., 1996, *A&AS*, 118, 595
- Valenti, J. A. & Fischer, D. A., 2005, *ApJS*, 159, 141
- Vogt, S.S., Allen, S.L. & Bigelow, B.C., et al. 1994, *SPIE*, 2198, 362
- Winn J. N. 2010, eprint arXiv:1001.2010
- Yelle, R., Lammer, H. & Ip, W.-H. 2008, *Space Sci. Rev.*, 139, 437

- 
- <sup>1</sup> Thüringer Landessternwarte, Sternwarte 5, Tautenburg, D-07778 Tautenburg, Germany
  - <sup>2</sup> Research and Scientific Support Department, ESTEC/ESA, PO Box 299, 2200 AG Noordwijk, The Netherlands
  - <sup>3</sup> Institut d'Astrophysique de Paris, UMR7095 CNRS, Université Pierre & Marie Curie, 98bis boulevard Arago, 75014 Paris, France
  - <sup>4</sup> Observatoire de l'Université de Genève, 51 chemin des Maillettes, 1290 Sauverny, Switzerland
  - <sup>5</sup> Laboratoire d'Astrophysique de Marseille, 38 rue Frédéric Joliot-Curie, 13388 Marseille cedex 13, France
  - <sup>6</sup> McDonald Observatory, University of Texas at Austin, Austin, TX 78712, USA
  - <sup>7</sup> Institute of Planetary Research, German Aerospace Center, Rutherfordstrasse 2, 12489 Berlin, Germany
  - <sup>8</sup> Université de Nice-Sophia Antipolis, CNRS UMR 6202, Observatoire de la Côte d'Azur, BP 4229, 06304 Nice Cedex 4, France
  - <sup>9</sup> Oxford Astrophysics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH
  - <sup>10</sup> LESIA, Observatoire de Paris, Place Jules Janssen, 92195 Meudon cedex, France
  - <sup>11</sup> Institut d'Astrophysique Spatiale, Université Paris XI, F-91405 Orsay, France
  - <sup>12</sup> Observatoire de Haute Provence, 04670 Saint Michel l'Observatoire, France
  - <sup>13</sup> LUTH, Observatoire de Paris, CNRS, Université Paris Diderot; 5 place Jules Janssen, 92195 Meudon, France
  - <sup>14</sup> Rheinisches Institut für Umweltforschung an der Universität zu Köln, Aachener Strasse 209, 50931, Germany
  - <sup>15</sup> Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
  - <sup>16</sup> University of Vienna, Institute of Astronomy, Türkenschanzstr. 17, A-1180 Vienna, Austria
  - <sup>17</sup> IAG, University of São Paulo, Brasil
  - <sup>18</sup> University of Liège, Allée du 6 août 17, Sart Tilman, Liège 1, Belgium
  - <sup>19</sup> European Southern Observatory, Alonso de Crdova 3107, Casilla 19001, Santiago de Chile, Chile
  - <sup>20</sup> Space Research Institute, Austrian Academy of Science, Schmiedlstr. 6, A-8042 Graz, Austria
  - <sup>21</sup> School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel
  - <sup>22</sup> Center for Astronomy and Astrophysics, TU Berlin, Hardenbergstr. 36, 10623 Berlin, Germany
  - <sup>23</sup> Dpto. de Astrofísica, Universidad de La Laguna, 38206 La Laguna, Tenerife, Spain
  - <sup>24</sup> Laboratoire d'Astronomie de Lille, Université de Lille 1, 1 impasse de l'Observatoire, 59000 Lille, France
  - <sup>25</sup> Institut de Mécanique Céleste et de Calcul des Ephémérides, UMR 8028 du CNRS, 77 avenue Denfert-Rochereau, 75014 Paris, France