SOPHIE velocimetry of Kepler transit candidates

XI. Kepler-412 system: probing the properties of a new inflated hot Jupiter

M. Deleuil, J.-M. Almenara, A. Santerne, S.C.C. Barros, M. Have, G. Hébrard, A.S. Bonomo, F. Bouchy, G. Brun, C. Damiani, R.F. Díaz, G. Montagnier, and C. Moutou

1 Aix Marseille Université, CNRS, LAM (Laboratoire d’Astrophysique de Marseille) UMR 7326, 13388, Marseille, France
e-mail: magali.deleuil@lam.fr
2 Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
3 NASA Ames Research Center, Moffett Field, CA 94035
4 Observatoire de Haute Provence, 04670 Saint Michel l’Observatoire, France
5 Institut d’Astrophysique de Paris, 98bis boulevard Arago, 75014 Paris, France
6 INAF Osservatorio Astrofisico di Torino, Via Osservatorio 20, 10025 Pino Torinese, Italy

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ABSTRACT

Context. Hot Jupiters are still a fascinating exoplanet population that presents a diversity we are still far from understanding. High-precision photometric observations combined with radial velocity measurements give us a unique opportunity to constrain their properties better, on both their internal structure and their atmospheric bulk properties.

Aims. We initiated a follow-up program of Kepler-released planet candidates with the goal of confirming the planetary nature of a number of them through radial velocity measurements. For those that successfully passed the radial velocity screening, we furthermore performed a detailed exploration of their properties to characterize the systems. As a byproduct, these systematic observations allow us to constrain the exoplanets’ occurrence rate.

Methods. We performed a complete analysis of the Kepler-412 system, listed as planet candidate KOI-202 in the Kepler catalog, by combining the Kepler observations from Q1 to Q15, to ground-based spectroscopic observations that allowed us to derive radial velocity measurements, together with the host star parameters and properties. We also analyzed the light curve to derive the star’s rotation period and the phase function of the planet, including the secondary eclipse.

Results. We secured the planetary nature of Kepler-412b. We found the planet has a mass of $0.939 \pm 0.005 \, M_{\text{Jup}}$ and a radius of $1.325 \pm 0.043 \, R_{\text{Jup}}$ which makes it a member of the bloated giant subgroup. It orbits its G3 V host star in 1.72 days. The system has an isochronal age of 5.1 Gyr, consistent with its moderate stellar activity as observed in the Kepler light curve and the rotation of the star of $17.2 \pm 1.6$ days. From the detected secondary we derived the day side temperature as a function of the geometric albedo. We estimated that the geometrical albedo $A_g$ should be between $0.094 \pm 0.015$ and $0.013_{-0.017}^{+0.017}$ and the brightness of the day side $2380_{-017}^{+83} \pm 40 \, K$. The measured night side flux corresponds to a night side brightness temperature of $2154 \pm 83 \, K$, much greater than what is expected for a planet with homogeneous heat redistribution. From the comparison to star and planet evolution models, we found that dissipation should operate in the deep interior of the planet. This modeling also shows that despite its inflated radius, the planet presents a noticeable amount of heavy elements, which accounts for a mass fraction of $0.11 \pm 0.04$.

Key words. stars; planetary systems - stars: fundamental parameters - techniques: photometry - techniques: radial velocities - techniques: spectroscopy - stars: individual: Kepler-412

1. Introduction

Space-based photometry observations of transiting planets have opened a new area for characterizing planets. Combined with high-precision radial velocity measurements, photometric observations allow deriving accurate planet parameters. In addition to a complete determination of the orbital parameters, it indeed provides valuable hints of the interior structure of the planet that might be related to the formation process and evolution history of the system. For the close-in giant planets, this has allowed the large diversity to be quantified better among what might appear as a single family at first glance. While most of these massive planets seem to possess a core whose typical mass is estimated at about $10 M_{\oplus}$ (Guillot et al., 2006; Miller & Fortney, 2011; Fortney et al., 2011), some such as Kepler-7b (Latham et al., 2010) appear to lack such a core, whereas some such as CoRoT-20b (Deleuil et al., 2012) present a surprisingly large amount of heavy material in their interior that could account for a core of a few hundreds Earth masses.

Probing the atmospheric properties of exoplanets is another situation that still remains challenging owing to the small amplitude of the planet’s atmospheric signatures. Significant advances have been, however, achieved during the past ten years from space-based observations in the near- or mid-infrared thanks to Spitzer observations (Grillmair et al., 2007, e.g.) or in some rare cases, from ground-based observations (Collier Cameron et al., 2002; Berdyugina et al., 2011). While the infrared spectral range gives access to the thermal emission, at visible wavelength, in principle, one can measure the reflected light of the atmosphere over the planet orbit and further obtain some hints on the energy budget of the planet. CoRoT and, even more, Kepler have proven such measurements are from now on possible for hot
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Jupiters, such as CoRoT-1 (Snellen et al., 2009; Alonso et al., 2009b) or Kepler-17b (Desert et al., 2011), but also Super-Earth ones (Sanchis-Ojeda et al., 2013), thanks to the long temporal coverage and the very high photometric precision that could be achieved from space-based observations. However, the number of these planets for which a noticeable geometric albedo has been measured remains limited today, confirming that hot Jupiters have very low reflectivity in visible, with an upper atmosphere likely lacking the bright clouds that are present in the atmosphere of the much colder giant planets in our solar system.

In this paper we confirm the planetary nature of one planet candidate in the Kepler catalog (Borucki et al., 2011) thanks to radial velocity observations and the planet’s subsequent characterization. This KOI, whose ID is KOI-202, is indeed one of the Kepler targets in the giant domain we observed during our radial velocity campaigns with the SOPHIE (Bouchy et al., 2011; Santerne et al., 2012) and ESPaDOnS spectrographs. It was identified as a potentially valuable target since a rough analysis of the Kepler light curve shows a clear secondary. This seemed a good opportunity to add a new member to the handful of giants for which the atmospheric properties could be explored.

Section 2 of this paper presents the complete set of observations that we used to assess the planetary nature of Kepler-412b and measure its parameters, that is, the complete sequences of Kepler observation and our follow-up ground-based spectroscopic observations. The combined analysis of both sets of data that allowed us to determine the system parameters is described in Section 3. The analysis of the phase curve and the secondary with the estimates of the planet’s albedo, redistribution factor, and brightness temperatures are presented in Section 4. The constraints we achieved on the planet’s internal structure are discussed in Section 5 and those on its atmospheric properties in Section 6. Section 7 summarizes our findings for this new system.

2. Observations and data reduction

2.1. Kepler photometric observations

Kepler-412b is one of the planet candidate listed in the Kepler data release of Feb. 2, 2011. From the data obtained in Q0 to Q5, Borucki et al. (2011) indeed report the detection of single periodic transits in the light curve of the star with a period of 1.72 days, a depth of 1%, and a duration of 2.1 hour, making this candidate a potential member of the giant-planet population. Table I gives the various IDs, coordinates and magnitudes of the host star as could be found from different catalogs.

For the study presented in this paper, we used the complete sequence of observations collected by the Kepler spacecraft during its more than four years of operation, that is, between May 13, 2009 and August 4, 2013 (Q1 to Q15). Most of the observations were performed in long cadence mode (temporal sampling of 29.4 min) but three quarters during which data were acquired in high cadence mode. The light curve of quarters Q1 to Q15 were downloaded from the Mikulski Archive at the Space Telescope Institute. These time series are reduced by the Photometric Analysis Kepler pipeline (version 8.01), which includes corrections for the main instrumental effects: background subtraction, barycentric, cosmic ray, and argabrightening effect (Jenkins et al., 2010). Figure I displays the Kepler observations where the quarters were normalized by the median value of the flux and gathered together. The transits are the most prominent features, but the photometric series shows a modulation of a few ppm related to a moderate stellar activity but with a sud-
As an additional verification, we also computed the light curve autocorrelation (McQuillan et al., 2013). We found a significant peak at $17.2 \pm 1.6$ days as shown in the bottom panel of Fig. 2. The two first harmonics at $34.6 \pm 1.4$ days and $51.5 \pm 1.6$ are also detected but do not clearly prevail. We noticed that this 17.2-day peak is ten times the period of the transit. Even though the transits were properly removed by using a model, we cannot completely exclude this peak being due to some residuals at the transit period. We checked how these values compared to the rotation period that is deduced from the projected rotation velocity $v \sin i$ and the star’s radius, assuming the star’s rotation axis is perpendicular to the line of sight, and the shaded areas are the associated $1\sigma$, $2\sigma$, and $3\sigma$ upper limit regions from the darkest to the lightest one.

2.2. Spectroscopic observations

Kepler-412 was observed with the SOPHIE spectrograph on the 1.93-m telescope at the Observatoire de Haute Provence (France) as part of our Kepler candidates follow-up program (Bouchy et al., 2011; Santerne et al., 2012). The observations were performed in high-efficiency mode without acquiring the simultaneous thorium-argon calibration, because we used the second fiber to monitor the Moon background light. A first set of spectra were acquired on July 2011 (see Table 2) and confirmed the planetary nature of Kepler-412b. The radial velocity measurements were in phase with the transit period with a semi-amplitude consistent with what is expected for a massive planet. In addition, we found no evidence of a close-by star, whether in the background or gravitationally bound to our target from the line-bisector analysis of the CCFs or from the use of cross-correlation masks constructed for different spectral

Table 1. Kepler-412 IDs, coordinates, and magnitudes.

| Kepler ID  | KOI ID   | USNO-B1 ID   | 2MASS ID | GSC2.3 ID |
|-----------|----------|--------------|----------|-----------|
| 7877496   | 202      | 1336-00316815 | 19042647-4340514 | N2E0000653 |

Coordinates

| RA (J2000) | Dec (J2000) |
|------------|-------------|
| 19:54:26.48 | 43:40:51.46 |

Magnitudes

| Filter | Mag  | Error |
|--------|------|-------|
| K$_b$  | 14.31|       |
| V$_b$  | 13.73| 0.24  |
| g$_b$  | 14.727| 0.04 |
| r$_b$  | 14.240| 0.04 |
| i$_b$  | 14.130| 0.04 |
| z$_b$  | 14.077| 0.04 |
| J$_c$  | 13.190| 0.027 |
| H$_c$  | 12.932| 0.033 |
| K$_c$  | 12.837| 0.031 |
| W1$_c$ | 12.824| 0.028 |
| W2$_c$ | 12.860| 0.031 |

a from the Kepler Input Catalog; b from the second-generation guide star catalog (Lasker et al., 2008); c from the 2-MASS catalog (Skrutskie et al., 2006); d from the WISE catalog (Cutri & et al., 2012).
types (Bouchy et al. 2008). These measurements were completed seven months later when the Kepler field became visible again from the ground. The complete RV measurements gives a semi-amplitude close to 140 m s\(^{-1}\) which corresponds to a Jupiter-mass companion.

| Table 2. Log of SOPHIE radial velocity observations |
|-----------------------------------------------|
| Date     | HJD     | \(v_{\text{rad}}\) \(\text{km} \text{s}^{-1}\) | \(\sigma_{v_{\text{rad}}}\) \(\text{km} \text{s}^{-1}\) | S/N 550 nm |
|----------|---------|-----------------|-----------------|-----------|
| 2011-07-25 | 2455767.53019 | -54.302 | 0.018 | 15 |
| 2011-07-31 | 2455773.49310 | -54.576 | 0.010 | 18 |
| 2011-07-31 | 2455774.43481 | -54.307 | 0.012 | 18 |
| 2012-02-26 | 2455983.66197 | -54.530 | 0.042 | 10 |
| 2012-03-24 | 2456010.62956 | -54.474 | 0.014 | 14 |
| 2012-03-26 | 2456012.61452 | -54.597 | 0.020 | 15 |

Once the planetary nature of Kepler-412b was confirmed, we observed the star with ESPaDOnS at the 3.6-m Canada-France-Hawaii Telescope in Mauna Kea as part of the 12AF95 program. The spectrograph provides spectral coverage of the 370 - 1000 nm region at a spectral resolution of 65000. The star was observed in ‘object+sky’ mode on July 2, 2012, in a series of short exposures totaling 15520 sec. We used the individual spectra reduced by the CFHT Upena/Libre-Esprit pipeline and co-added them once they were set in the rest frame. This results in a spectrum with a S/N of 110 in the continuum per resolution element at 6000 Å.

The spectral analysis was carried out with the semi-automatic software package VWA (Bruntt et al. 2010a,b), which derives the atmospheric parameters by minimizing the correlations of the Fei abundance with both equivalent width and excitation potential. We used the \(v_{\text{sin} \, i}\) derived from the SOPHIE CCFs and later checked its value and the \(v_{\text{macro}}\) one on a set of isolated spectral lines. An estimate the surface gravity was derived from the Fei and Feii agreement, but we also carried out an independent estimate from the pressure-sensitive lines: the Mg b1 lines and the Ca i ones at 6122Å and 6262Å. The abundances of the elements are given in Table 3 from metals with more than ten lines with measured abundances. Taking uncertainty on \(T_{\text{eff}}\), \(\log g\), and \(v_{\text{mic}}\) into account, we calculated a mean metallicity of \([\text{M}/\text{H}] = 0.27 \pm 0.12\). The final atmospheric parameters of the host star are given in Table 4.

To determine the star’s fundamental parameters: mass, radius, and age, we compared the atmospheric parameters \(T_{\text{eff}}\) and [Fe/H] and the stellar density from the transit fit to a two-dimensional grid of STAREVOL evolutionary tracks of stellar mass and metallicity (Palacios, priv. com., Lagarde et al.2012). We calculate the probability distribution function by minimizing the distance to the grid of evolutionary tracks from the Monte Carlo realizations of the atmospheric parameters and their associated errors and the distribution of stellar density provided by the transit modeling (see Sect. 3). This yields \(M_\star = 1.15 \pm 0.06 \, M_\odot\), and \(R_\star = 1.31 \pm 0.03 \, R_\odot\). These values are consistent with those obtained from the complete data set modeling performed with PASTIS and given in Table 4.

With an age of 5.1 \(\pm 1.2\) Gyr, the star is well on the main-sequence phase, which makes it a mature system. The moderate star’s rotation period we derived from the light curve analysis also agrees with such an evolutionary status. Inspection of the spectra reveals no emission in the Ca ii H and K lines or other photospheric lines but a detectable Li i doublet line. According to Sestito & Randich (2005), the measured Li i abundance of 2.03, points toward an age for the star > 1 Gyr. All the age indicators, including the moderate photometric variation observed in the light curve of the host star, agree and confirm the inferred stellar age.

| Table 3. Relative abundances of the main elements |
|-----------------------------------------------|
| Element | Abundances | Nb lines |
|--------|------------|----------|
| Li i   | 0.98 \(\pm 0.10\) | 3 |
| O i    | 0.26 \(\pm 0.10\) | 3 |
| Na i   | 0.48 \(\pm 0.10\) | 2 |
| Si i   | 0.28 \(\pm 0.08\) | 13 |
| Ca i   | 0.27 \(\pm 0.09\) | 5 |
| Ti i   | 0.22 \(\pm 0.09\) | 14 |
| Ti ii  | 0.44 \(\pm 0.08\) | 6 |
| Cr i   | 0.19 \(\pm 0.08\) | 5 |
| Mn i   | 0.43 \(\pm 0.10\) | 5 |
| Fe i   | 0.26 \(\pm 0.08\) | 104 |
| Fe ii  | 0.29 \(\pm 0.09\) | 16 |
| Co i   | 0.42 \(\pm 0.09\) | 5 |
| Ni i   | 0.32 \(\pm 0.08\) | 34 |

3. Kepler-412 system analysis

The properties of the Kepler-412 system were derived from a joint analysis of the light curve, the radial velocity measurements, and the star’s properties. This analysis was carried out with the Planet Analysis and Small Transit Investigation Software (PASTIS) (Díaz et al. 2013a). Primarily developed for planet validation (Moutou et al. 2014), the software models all the observables from the light curve, the spectral energy distribution and radial velocity measurements in a self-consistent way and further provides rigorous estimate of the confidence regions for all parameters (see Díaz et al. 2013b, e.g.).

For the photometric time-series analysis, we kept the light curves acquired in long cadence but used the short cadence ones to tune the oversampling parameter following the method that Kipping & Bakos (2011) originally advocated, and which was later further developed by Southworth (2012). We first derived the \(a/\text{R}_\star, \text{R}_\star/\text{R}_\odot\), and the inclination \(i\) from the transits acquired in short cadence. We then did the same exercise on long cadence transits, using different values of the oversampling for the model until we found the same values of the transit parameters than those derived from short cadence. We found seven as the optimal value and the modeling was performed on long cadence light curves oversampled to this value.

The light curves from the different quarters were gathered by seasons to account for change in the contamination value and in the noise budget from one season to another. For the quarters of Season 0, we used the contamination value given in the light curve fits header. For the others seasons, the contamination values were let as free parameters in the fitting process. Indeed, some authors (Díaz et al. 2013b, e.g.) report that the crowding factors in the KIC, and beyond that the contamination ones, might be erroneous, which could lead to wrong estimates of the transit depth. In the case of Kepler-412, while the dispersion in short- and 3.8% for Seasons 2 and 3, respectively. We thus choose not to adopt the Kepler contamination values, but let them vary.

To obtain a clean light curve for the light curve modeling, we reproduced the low-frequency variations of the light curve derived from the periodogram (see Sec. 2.1), using a Savitzky-
The normalized phase-folded light curve was modeled using the EBOP code (Popper & Etzel, 1981) provided in the JKTEBOP package (Southworth, 2011). It takes the mutual eclipses of both members of the system, the tidal ellipsoidal distortion induced by the planet and the reflected light of both components of the system into account. We also included the Doppler beaming and we used the formalism described in Bloemen et al. (2011). The radial velocities were described by an eccentric Keplerian orbit. The model for the SED modeling was calculated by interpolating the PHOENIX/BT-Settl synthetic spectral library (Allard et al., 2012), scaled to the distance and the color index $E(B-V)$ that were set as free parameters.

The three sets of data were then fitted simultaneously. To account for systematics errors in each data set that could result in an additional noise, we also introduced a jitter value for each data set. In total, the model accounts for 31 free parameters. The parameters of the model were adjusted to the data using a MCMC algorithm with an adaptive step size, as described in detail by Diaz et al. (2013a). Thirty-five chains of 200 000 steps were carried out with initial values randomly drawn from the joint priors. For the latter, we used uniform or Jeffreys distributions for the priors but the stellar density, the $T_{\text{eff}}$, and the metallicity, which were described by a normal distribution. In all cases, the width of the distribution was chosen large enough not to bias the posterior. For the transit parameters, epoch, and period, we used Batalha et al. (2013) values for the priors. For the parameters related to the host star we used the values obtained from the spectroscopic analysis (Sect. 2.2).

In PASTIS, the burn-in interval of each of the chains is computed by comparing the mean and standard deviation of the last 10% of the chain to preceding fractions until a significant difference is found. The correlation length is computed for each of the parameters, and the maximum value is retained and used to thin the chain so that the samples in the chain are independent. The non-convergence is verified using the Gelman and Rubin statistics, and only the chains that show no signs of converging are merged into a single chain. In the case of Kepler-412 sytem, from the initial 35 chains, 32 passed the Gelman and Rubin statistics test and were used to make the final merged chain. The burn-in interval was between ~ 34 to 50 %, and the correlation lengths for each chain were between ~ 1110 to 6900 points, depending on the chain. The median values obtained for the fitted parameters of the Kepler-412 system through this modeling approach are given in Table 6. This table also gives derived parameters and the 68.3% central confidence interval associated to all parameters. Figure 3 shows the corresponding best-fit model for the transit, the radial velocity measurements, and the SED. We checked the consistency of the various parameters of the best-fit model with those inferred from analyses used as priors or complementary ones.

We verified whether our fitted quadratic limb-darkening coefficients agree with the theoretical ones, derived from the photospheric parameters (see Sect. 2.2). Using the tables of Claret & Bloemen (2011), the expected limb-darkening coefficients are $u_0 = 0.395 \pm 0.015$ and $u_0 = 0.2702 \pm 0.0075$. The best values (Table 6) agree within the error bars with the predicted ones. In our modeling, the light curve and the RV measurements yield independent estimates of the mass ratio that we went on to compare. The mass ratio derived from the ellipsoidal variations is $q = 0.00078 \pm 0.00014$, a value nicely consistent with the one calculated from the planet’s mass derived from RV amplitude and the star’s mass, which is $0.000772 \pm 0.000063$.

The eccentricity was set as a free parameter. We found a negligible eccentricity $e < 0.0377$ at 99% probability in-
tival (0.0062 at 68.3%). This result is constrained by both the SOPHIE radial velocity measurements and the secondary eclipse. We thus decided on a circular orbit.

We next compared the stellar parameters derived from the spectroscopic analysis and used as priors (Sect. 2.2) to those fitted in PASTIS through the complete modeling of all data sets, that is, \( T_{\text{eff}} = 5866 \pm 60 \text{ K} \) and metallicity \( [M/H] = 0.20 \pm 0.12 \). Those values that are within 1\( \sigma \) of our spectroscopic values as shown in Fig. 4. As usually, the star’s mass and radius are better constrained from the transit fitting than by the surface gravity. From the star’s mass and radius estimated by the complete modeling carried out with PASTIS, that is, \( M = 1.17 \pm 0.09 \; M_\odot \) and \( R = 1.28 \pm 0.03 \; R_\odot \), we derived a stellar surface gravity, \( \log g = 4.285 \pm 0.015 \), in good agreement with the spectroscopic value.

In conclusion, Kepler-412 system appears to be composed of a solar-type star, slightly enriched in metals, and of a Jupiter-like planet with \( M_p = 0.939 \pm 0.085 \; M_{\text{Jup}} \) and \( R_p = 1.325 \pm 0.043 \; R_{\text{Jup}} \) on an almost circular orbit.

### 4. Secondary eclipse and planetary phase function

Kepler-412 phase-folded light curve shows a clear phase function and a significant secondary eclipse (Fig. 5), which were both modeled in the fitting procedure (see Sect. 3). This offers the opportunity to probe the overall physical properties of the planet’s atmosphere.

From the eclipse depth, one can set constraints on the geometric albedo and the day side temperature. To that purpose, we used the same methodology as presented in [Santerne et al., 2011] with the formalism developed by [Cowan & Agol, 2011], which assumes the planet is tidally locked. This formalism takes \( \varepsilon \), the fraction of the energy which is received by the day side of the planet and transferred to its night side into account. We recall that \( \varepsilon = 0 \) when the day side re-emits the energy received and when there is no heat transfer to the night side, and \( \varepsilon = 1 \) when the energy is homogeneously redistributed over the whole planet’s surface. While this methodology has already been followed by several authors (e.g., [Mazeh et al., 2012], [Esteves et al., 2013]), for the sake of clarity, we recall the main equations used in this calculation. The equilibrium day side temperature is a function of both the redistribution factor and the Bond albedo \( A_B \):

\[
T_{\text{eq,D}} = T_{\text{eff,f}} \left( \frac{R_p}{a} \right)^{1/2} \left[ \left( \frac{2}{3} - \frac{5}{12} \varepsilon \right) \left( 1 - A_B \right) \right]^{1/4},
\]

and the night side temperature is given as:

\[
T_{\text{eq,N}} = T_{\text{eff,f}} \left( \frac{R_p}{a} \right)^{1/2} \left[ \left( \frac{\varepsilon}{4} \right) \left( 1 - A_B \right) \right]^{1/4}.
\]

For the two extreme cases, \( \varepsilon = 0 \) and \( \varepsilon = 1 \), of a non reflective planet (\( A_B = 0 \)), we calculated the range in equilibrium temperature of the planet’s day side. We found the equilibrium temperature of the day side varies from 1828 K in the case of a complete redistribution to 2336 K when there is a complete re-emission from the day side. From the measured eclipse depth and assuming the planet radiates as a black body, we then estimated the planet’s brightness temperature in the Kepler bandpass:

\[
F_{\text{ecl}} = \left( \frac{R_p}{R} \right)^2 \left[ \frac{B_1(T_{\text{eff,D}}) T_{\text{eff,D}} d\lambda}{\int T_{\text{eff}} F_{\lambda} d\lambda} + A_1 \left( \frac{R_p}{a} \right)^2 \right].
\]

To that purpose, we used the synthetic spectrum of a solar-like star calculated from Kurucz’s models (Kurucz, 1993) to calculate the stellar flux, and we integrated it in the Kepler bandpass. In the unrealistic case where the thermal emission is solely responsible for the secondary eclipse, we found a brightness temperature of the day side of 2380 \pm 40 \text{ K}. We then calculated the planet’s brightness temperature in the Kepler bandpass (Fig. 5), in the more realistic case where both the reflected light and the thermal emission contribute to the eclipse depth.

We found that, in the range defined by the equilibrium temperatures, the geometrical albedo is between 0.013 \( \pm 0.017 \) when all the energy received by the planet day side is re-radiated, and 0.094 \( \pm 0.015 \) in the extreme case where the eclipse depth in the Kepler bandpass is due to the reflected energy alone. This value is an upper limit since, even in the visible, one indeed expects...
the thermal component of the planet’s emission to contribute to the phase function.

The phase function exhibits a significant amplitude that provides information on the night side of the planet. From the difference between the depth of the eclipse and the amplitude of the phase function, we derived a significant night side flux $F_n = 18.7 \pm 7.3$ ppm. Using this value, assuming a black body emission from the planet, and using PHOENIX/BT-Settl synthetic spectra for the star, we found the planet night side brightness emission of $T_{B,N} = 2154 \pm 83$ K in the Kepler bandpass. In principle, this might allow evaluation of the redistribution factor between the two planet’s faces. Figure 7 shows how this night side temperature compares with the expected equilibrium night side temperature (from eqn. 2) as a function of the redistribution factor, using the range of values we obtained for the geometrical albedo. The measured night side temperature is clearly greater than one would expect even in the case of a planet with a homogeneous heat distribution. There is indeed no overlap between the two curves for the night temperature. A similar situation has been recently reported in the case of TrES-2 (Esteves et al., 2013). As suggested by these authors, this discrepancy might be related to the physical properties of the planet’s emitting layers probed in the Kepler bandpass, their temperature being higher than the equilibrium temperature. Another possibility would be that an additional source of heating in the planet interior, not included in the simple model we used, might be responsible for this high temperature of the night side of the planet.

We noted that the phase light curve in Figure 5 might exhibit an eastward asymmetry. However, we found that this suspected asymmetry is not significant and did not try to assess it to atmospheric circulation properties.

5. Kepler-412b internal structure

With a mass of 0.939 $M_{Jup}$, a radius of 1.325 $R_{Jup}$, and an inferred density of $0.50 \pm 0.05$ g cm$^{-3}$, Kepler-412b belongs to the inflated class of the hot Jupiter population. Combined stellar (CESAM [Morel & Lebreton, 2008]) and planetary (CEPAM [Guillot & Morel, 1995; Guillot, 2010]) evolution models of the Kepler-412 system were calculated with SET (see Guillot & Havel [2011], Havel et al. [2011]). We used a MCMC algorithm to obtain posterior probability distributions of the bulk composition of the planet. The results are presented in terms of planetary radii as a function of age in Figure 8.

Planetary evolution models are calculated in two cases: a “standard” case where the planet is assumed to be made of a central rocky core and a solar-composition envelope (Fig. 8), and a “dissipated-energy” model in which, in addition to the standard case, a fraction (0.25%) of the incoming stellar light is assumed to be converted into kinetic energy and then dissipated at the center of the planet (see Almenara et al. [2013] for more details).

Only models with dissipation provide solutions for the planetary radius that match the available constraints, resulting in a core mass of $31 \pm 11 M_{\oplus}$, which translates into a heavy element mass fraction of $0.11 \pm 0.04$\footnote{However, we do not know precisely}. These numbers come from independent MCMC 1-D distributions

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**Fig. 6.** Geometric albedo as a function of the planet day side brightness temperature from equation (3). The vertical lines correspond to the extreme values for a planet that absorbs all the incoming flux; $\epsilon = 0$ when all the energy received on the day side is reemitted; $\epsilon = 1$ when all the energy received on the day side is fully re-distributed. The gray band indicates the albedo values allowed by the $1 \sigma$ uncertainty on the occultation depth, which is assumed to be the dominant one.

**Fig. 7.** The expected equilibrium temperature of the night side (blue) as a function of redistribution factor from eqn. 1. The dark band gives the limits that correspond to the range of values for the geometrical albedo. The lighter band indicates the $1 \sigma$ uncertainties of each curve, including the uncertainties in the star’s temperature and in $R_*/a$. The night side temperature and its associated uncertainty estimated from the night flux is plotted in gray.

**Table 4.** Fitted and derived parameters for the secondary and the phase curve.

| Parameter | Description | Value ± Uncertainty |
|-----------|-------------|---------------------|
| $F_{\text{a}d}$ | Depth of secondary eclipse [ppm] | 47.4 ± 7.4 |
| $A_{\text{a}llop}$ | Amplitude of the ellipsoidal variation [ppm] | 10.2 ± 2.5 |
| $A_{\text{a}r}$ | Amplitude of the reflected light [ppm] | 14.2 ± 1.6 |
| $A_{\text{a}b}$ | Amplitude of the beaming effect [ppm] | 1.81 ± 0.14 |
| $A_{\text{a}p}$ | Amplitude of the phase function [ppm] | 28.8 ± 3.2 |
| $F_n$ | Night side flux [ppm] | 18.7 ± 7.3 |

**Derived day side parameters**

| Parameter | Description | Value ± Uncertainty |
|-----------|-------------|---------------------|
| $A_{g,\text{max}}$ | Geometric albedo | 0.094 ± 0.015 |
| $A_{g,\text{min}}$ | Geometric albedo | 0.013 ± 0.0015 |
| $T_{\text{eq,min}}$ | Equilibrium temperature ($\epsilon = 1$) [K] | 1828 ± 22 |
| $T_{\text{eq,max}}$ | Equilibrium temperature ($\epsilon = 0$) [K] | 2336 ± 27 |
| $T_{\text{D,N}}$ | Brightness day side temperature [K] | 2380 ± 40 |

**Derived night side parameter**

| Parameter | Description | Value ± Uncertainty |
|-----------|-------------|---------------------|
| $T_{\text{B,N}}$ | Night side temperature [K] | 2154 ± 83 |

*Calculated using Mazeh & Faigler (2010) formalism.*
how much the planet could actually dissipate in its interior (e.g. Guillot & Showman, 2002; Batygin et al., 2011; Laughlin et al., 2011), reducing by two (respectively 5 and 10) the amount of energy dissipated in the planet’s interior, moves the $0.3 M_\oplus$ line from 1.444 to 1.391 $R_\text{Jup}$ (resp. 1.332 and 1.294) (Fig. 8), which corresponds to a 3.7% reduction in radius (resp. 7.7% and 10%). It is therefore possible that Kepler-412b has no core at all. On the other hand, the high metallicity of the star tends to indicate that the planet should probably have a certain amount of heavy elements (Guillot et al., 2006). Whether they are dispersed in the envelope (Baraffe et al., 2008) or are all condensed into the core is not clear, but does not significantly affect our results.

6. Kepler-412 system in context

At visible wavelengths, phase curve and secondary eclipse have been measured for only a dozen validated planetary systems only (Table 5). Two are CoRoT planets, but the large majority of the sample are systems found from Kepler light curves. All these planets are close-in giants that cover a range of masses over nearly one order of magnitude, from Kepler-12b whose mass is only 0.43$M_\text{Jup}$ to KOI-13b, which has a mass greater than 8 $M_\text{Jup}$. All of them also present a measured geometric albedo that is much lower than giant planets in the Solar System. Their low albedo is in agreement with models of irradiated planet, it is difficult to draw firm conclusions. Definitely, this tendency would require a much larger sample to be confirmed.

7. Summary

Radial velocity measurements carried out with the SOPHIE high-precision spectrograph at the OHP allowed us to secure the planetary nature of Kepler-412b, a planet candidate whose transits were detected in the Kepler light curves. We also derived its fundamental parameters by performing the combined analysis of the radial velocity measurements, the complete series of Kepler quarters (Q1 to Q15), and the host star properties, through a Bayesian approach implemented in the PASTIS software. We found that with a mass of 0.939$M_\text{Jup}$ and a radius of 1.325$R_\text{Jup}$, the planet is a new member of the hot Jupiter population with an inflated radius. For this low-density planet, we...
found that models with dissipation are required in order to reproduce the planet’s radius at its current age. The model suggests there is a significant amount of heavy elements in the interior of the planet, maybe in the form of a massive core of about 31\(M_\oplus\), with an extended envelope of H-He.

From the phase function and the secondary eclipse, we derived a very low geometric albedo less than 0.1, and a night side temperature much higher than the maximum hemisphere-averaged expected equilibrium one. The Kepler data alone do not give us strong leverage on the temperature structure of the planet’s atmosphere and do not allow us to investigate it in detail as it has been done for some of the Kepler planets with additional measurements of the eclipse in the near infrared. However, the comparison to other close-in giants shows a possible correlation between the secondary detection and one of the mechanisms that might be responsible for the radius anomaly. This needs to be validated with a much larger sample, but if confirmed, it could suggest that the differences in atmospheric properties of close-in giants with a marked inflated radius and the non-inflated ones is also reflected in their phase light curve properties.

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### Table 5. Planetary systems with phase curve and/or secondary detected.

| System      | T eff  | a     | $T_{eq}$ | $M_p$ | $R_p$ | P     |
|-------------|--------|-------|----------|-------|-------|-------|
| Kepler-5    | 6297 ± 60 | 0.05064 ± 0.0018 | 1752 ± 17 | 2.112 | 1.431 | 3.5484 |
| Kepler-6    | 5647 ± 44 | 0.04561 ± 0.0006 | 1451 ± 16 | 0.668 | 1.323 | 3.2347 |
| Kepler-7    | 5933 ± 44 | 0.06246 ± 0.00046 | 1586 ± 13 | 1.443 | 1.614 | 4.8854 |
| Kepler-8    | 6210 ± 150 | 0.04833 ± 0.002 | 1638 ± 40 | 0.583 | 1.419 | 3.5225 |
| Kepler-12   | 3947 ± 100 | 0.05563 ± 0.007 | 1477 ± 26 | 0.432 | 1.695 | 4.438  |
| Kepler-17   | 5781 ± 85 | 0.0268 ± 0.0005 | 1655 ± 40 | 2.477 | 1.330 | 1.4857 |
| Kepler-41   | 5620 ± 140 | 0.0303 ± 0.0009 | 1567 ± 41 | 0.540 | 1.240 | 1.8555 |
| KOI-13      | 8500 ± 400 | 0.0514 ± 0.0020 | 2885 ± 140 | 8.500 | 2.042 | 3.5225 |
| HAT-P-7     | 6350 ± 80 | 0.0355 ± 0.0044 | 2139 ± 27 | 1.779 | 1.363 | 2.204  |
| TRES-2      | 5850 ± 50 | 0.0367 ± 0.0013 | 1444 ± 13 | 1.193 | 1.224 | 2.470  |
| CoRoT-16    | 5950 ± 150 | 0.0254 ± 0.0004 | 1896 ± 52 | 1.037 | 1.490 | 1.5089 |
| CoRoT-11.8  | 5625 ± 120 | 0.0281 ± 0.0004 | 1536 ± 35 | 3.273 | 1.466 | 1.742  |

**Notes.**

1. Koch et al. (2010)
2. Esteves et al. (2013)
3. Heng & Demory (2013)
4. Dunham et al. (2010)
5. Demory et al. (2011)
6. Jenkins et al. (2010)
7. Fortney et al. (2011)
8. Desert et al. (2011)
9. Bonomo et al. (2012)
10. Santerne et al. (2011)
11. Bonomo et al., to be submitted.
12. Szabo et al. (2011)
13. Mazeh et al. (2012)
14. Christiansen et al. (2010)
15. Barclay et al. (2012)
16. Alonso et al. (2009a)
17. Snellen et al. (2009)
18. Alonso et al. (2009b)

In some cases, asymmetric error bars have been symmetrized.
Table 6. Kepler-412 system: planet and star parameters.

| Parameter                                                                 | Value                                                                 |
|--------------------------------------------------------------------------|----------------------------------------------------------------------|
| **Ephemeris and orbital parameters:**                                    |                                                                     |
| Planet orbital period $P$ [days]                                         | 1.720861232 ± 4.7 $10^{-8}$                                         |
| Primary transit epoch $T_0$ [BJD-2400000]                                | 54966.021033 ± 2.3 $10^{-3}$                                         |
| Orbital eccentricity $e$                                                 | 0.0038 ± 0.0008                                                     |
| Argument of periastron $\omega$ [deg]                                   | 125 $^{+150}_{-49}$                                                |
| Orbital inclination $i$ [deg]                                            | 80.89 ± 0.20                                                       |
| Primary impact parameter $P_{\text{imp}}$                               | 0.781 $^{+0.008}_{-0.010}$                                         |
| Primary transit duration $T_{\text{tr}}$ [h]                            | 2.077 ± 0.015                                                      |
| **Fitted transit-related parameters:**                                  |                                                                     |
| Scaled semi-major axis $a/R_*$                                          | 4.947 ± 0.056                                                      |
| Radius ratio $R_p/R_*$                                                  | 0.1058 ± 0.0023                                                    |
| Quadratic limb darkening coefficient $u_a$                              | 0.18 ± 0.44                                                       |
| Quadratic limb darkening coefficient $u_b$                              | 0.51 ± 0.58                                                       |
| $R_p/a$                                                                  | 0.02145 ± 0.00052                                                  |
| **Data-related parameters:**                                            |                                                                     |
| Kepler season 0 contamination [%]                                       | 5.47                                                               |
| Kepler season 1 contamination [%]                                       | 5.24 ± 0.15                                                       |
| Kepler season 2 contamination [%]                                       | 3.42 ± 0.17                                                       |
| Kepler season 3 contamination [%]                                       | 5.69 ± 0.13                                                       |
| Kepler season 0 jitter [ppm]                                            | 96.3 ± 3.4                                                        |
| Kepler season 1 jitter [ppm]                                            | 117.1 ± 2.6                                                       |
| Kepler season 2 jitter [ppm]                                            | 114.5 ± 4.0                                                       |
| Kepler season 3 jitter [ppm]                                            | 90.6 ± 3.1                                                        |
| SOPHIE jitter [ m s$^{-1}$]                                             | 12.4 $^{+16.0}_{-9.9}$                                           |
| SED jitter [mags]                                                       | 0.028 ± 0.022                                                     |
| **Fitted RV-related parameters:**                                       |                                                                     |
| Radial velocity semi-amplitude $K$ [km s$^{-1}$]                        | 0.142 ± 0.011                                                     |
| **Spectroscopic parameters:**                                           |                                                                     |
| Effective temperature $T_{\text{eff}}$ [K]                             | 5750 ± 90                                                         |
| Surface gravity log $g$ [dex]                                           | 4.30 ± 0.07                                                       |
| Metallicity [Fe/H] [dex]                                                | 0.27 ± 0.12                                                       |
| Stellar rotational velocity $v\sin i$ [km s$^{-1}$]                    | 5.0 ± 1.0                                                         |
| Stellar microturbulence $v_{\text{mic}}$ [km s$^{-1}$]                 | 1.0 ± 0.1                                                         |
| Stellar macroturbulence $v_{\text{macro}}$ [km s$^{-1}$]               | 2.86 ± 1.0                                                        |
| Spectral type                                                          | G3 V                                                               |
| **Stellar physical parameters from combined analysis:**                 |                                                                     |
| $M_1^{1/3}/R_*$ [solar units]                                           | 0.8184 ± 0.0092                                                   |
| Stellar density $\rho_*$ [solar units]                                  | 0.547 ± 0.018                                                     |
| Star mass $M_*$                                                        | 1.167 ± 0.091                                                     |
| Star radius $R_*$                                                      | 1.287 ± 0.035                                                     |
| Stellar rotation period $P_{\text{rot}}$ [days]                        | 17.2 ± 1.6                                                        |
| Age of the star [Gyr]                                                  | 5.1 ± 1.7                                                         |
| Distance of the system [kpc]                                            | 1.056 ± 0.036                                                     |
| Interstellar extinction $E(B-V)$                                       | 0.013 ± 0.015                                                     |
| **Planetary parameters from combined analysis:**                        |                                                                     |
| Orbital semi-major axis $a$ [AU]                                        | 0.02959 ± 0.00072                                                |
| Planet mass $M_p$ [M$_J$]                                               | 0.939 ± 0.085                                                     |
| Planet radius $R_p$ [R$_J$]                                             | 1.325 ± 0.043                                                     |
| Planet density $\rho_p$ [g cm$^{-3}$]                                  | 0.501 ± 0.051                                                     |

\[ a = \frac{a \sin i \cdot 1 - c^2}{1 - e \sin \omega} \]

\[ b = \frac{b \sin i \cdot 1 + c^2}{1 - e \sin \omega} \]

\[ b \] Radius and mass of Jupiter taken as 71492 km and 1.8986×$10^{30}$ g, respectively.