SOPHIE velocimetry of *Kepler* transit candidates: a joint photometric, spectroscopic and dynamical analysis of the Kepler-117 system

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We present the analysis of the multi-planetary system Kepler-117, which is part of our program of observations of *Kepler* planets. This system is composed of a ~30 Earth-mass planet in a ~19 days orbit and a ~2 Jupiter-mass planet orbiting in ~51 days. Both the orbits have low eccentricity. The planets are not close to an exact low-order mean motion resonance, but exhibit significant transit timing variations (TTVs) nevertheless. We perform a combined Markov Chain Monte Carlo fit on all the available data: the *Kepler* photometry, the TTVs, the radial velocities we obtained with *SOPHIE*/OHP and the stellar parameters. The prime result is that the modelling of the TTVs allows to increase the precision on the system parameters which are not constrained by the radial velocities alone.

Context

- **Multiple planet systems** offer insights on their dynamical history (e.g. Batygin & Morbidelli 2013) and can show **transit timing variations** (TTVs: Agol et al. 2005).

- **TTVs** are a powerful tool for
  1) the detection of non-transiting planets
  2) the determination of planetary masses (e.g. Holman et al. 2010)
  3) tracking stellar activity (e.g. Barros et al. 2013).

- Unaccounted-for TTVs cause an underestimation of the uncertainty on the stellar density derived from the photometry (Kipping 2014).

- The planets Kepler-117 b and c have been validated by Rowe et al. (2014) with a confidence level of more than 99%, after passing several tests for the identification of false positives.

- Kepler-117 has been observed in the context of our **program of ground-based follow-up** of *Kepler* planetary candidates (e.g. Bouchy et al. 2011, **see poster P1.21**).

Data

- ***Kepler* photometry**, from quarter 1 to 3 (long cadence data, 29.4 minutes) and from 4 to 17 (short cadence, 58.5 seconds).

- **Radial velocities** obtained with the *SOPHIE* spectrograph at the Observatoire de Haute-Provence.
15 spectra acquired between 2012 and 2013 (high efficiency mode, spectral resolution ≈ 39000).

- **Spectrum of the host star** obtained by removing the Doppler shifts for the radial velocity spectra. Stellar **atmospheric parameters** derived with the VWA package (e.g. Bruntt e. al. 2010).

Stellar parameters		
$T_{\rm eff}$ [K]	6150 ± 110	
Metallicity [Fe/H]	-0.04 ± 0.10	
Derived $\log g$	4.10 ± 0.02	
Stellar density $\rho_\star$ [$\rho_\odot$]	$0.29^{+0.01}_{-0.02}$	
Stellar mass [$M_\odot$]	$1.13^{+0.13}_{-0.02}$	
Stellar radius [$R_\odot$]	1.61 ± 0.05	
Planet parameters	*Kepler-117b*	*Kepler-117c*
Orbital period P [days]	$18.80 \pm 7.5 \times 10^{-6}$	$50.79 \pm 1.4 \times 10^{-5}$
Orbital eccentricity e	0.05 ± 0.01	0.03 ± 0.003
Planet mass M_p [M_J]	0.09 ± 0.03	1.84 ± 0.18
Planet radius R_p[R_J]	0.72 ± 0.02	1.10 ± 0.04
Planet density ρ_p [$g\ cm^{-3}$]	0.30 ± 0.11	1.74 ± 0.18

Table 1: Kepler-117 main parameters

Method

- Transit times fitted with a procedure similar to the one discussed in Barros et al. (2011).

- The photometry, the radial velocities and the stellar parameters are jointly fitted with the Bayesian-oriented Planet Analysis and Small Transit Investigation Software (**PASTIS**: Díaz et al. 2014).

- The parameters posteriors have been sampled with a **Markov Chain Monte Carlo algorithm. The TTVs modelling has been included,** as well, using the orbital dynamics software *mercury* (Chambers 1999).

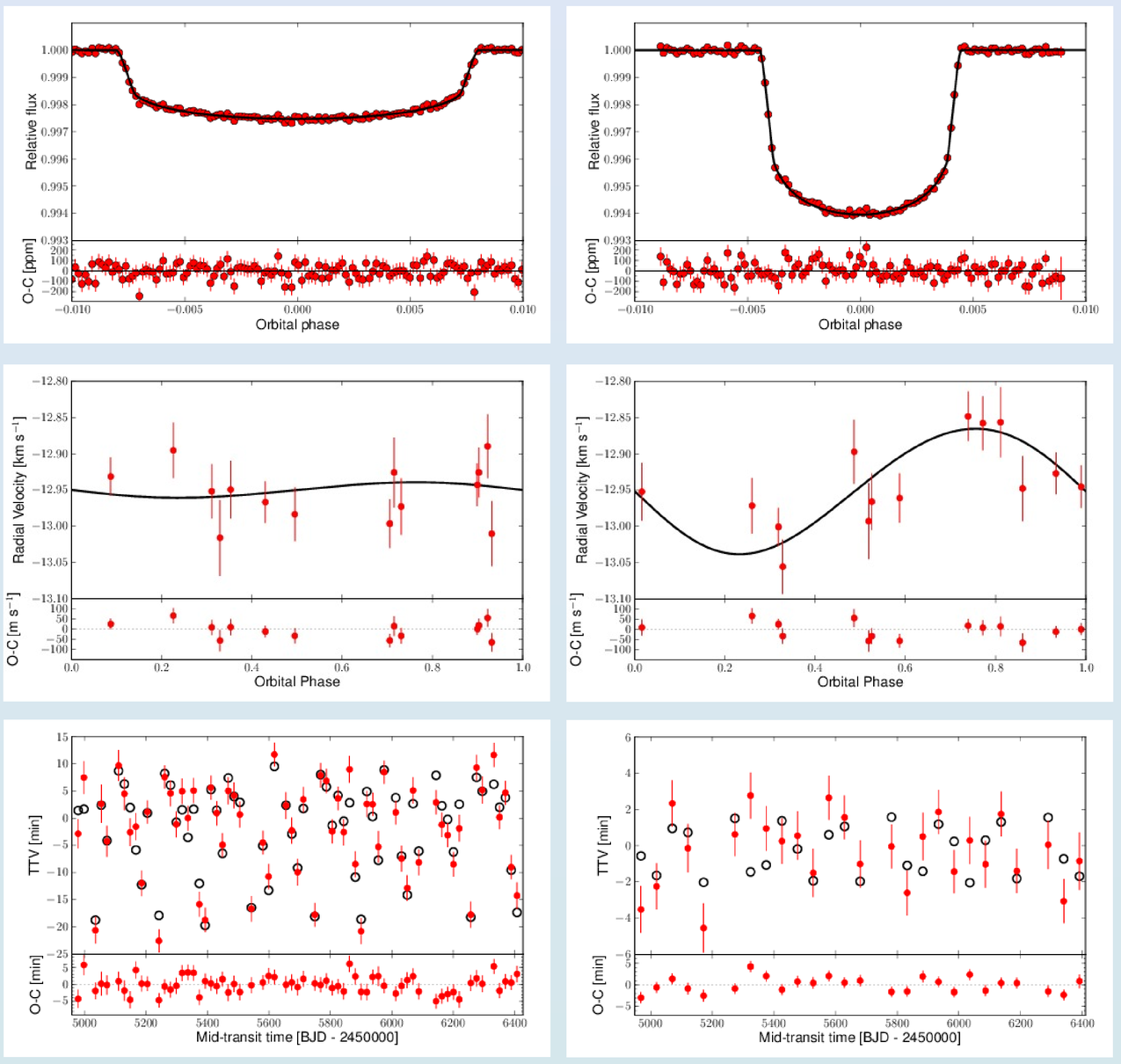

Figure 1. *Top:* phase-folded plot of the best transit model of planet b (left) and c (right), over the short cadence data. In black the model, in red the data binned every hundredth of orbital phase. *Centre:* the same for the radial velocities. *Bottom:* The TTVs of planet b (left) and those of planet c (right). For each plot, the lower panel shows the residuals as observed minus calculated (O−C) points.

Results

- The system exhibits **significant TTVs** even if the period ratio is not close to an exact low-order mean motion resonance.

- The inclusion of the TTVs in the combined fit **allows to fit parameters that are poorly constrained with the RVs only** (table 1 – Bruno et al., submitted)**.**

→ **the mass of planet b,** whose radial velocity amplitude (~11 m/s) is close to the limit of efficiency of *SOPHIE* for faint magnitudes (fig.1, middle-left plot), **is precisely determined.**

- With a mass ratio close to 20 and similar radii, the two planets have **considerably different densities.**

References
Agol, E., Steffen, J., Sari, R., & Clarkson, W. 2005, MNRAS, 359, 567
Barros, S. C. C., Boué, G., Gibson, N. P., et al. 2013, MNRAS, 430, 3032
Batygin, K. & Morbidelli, A. 2013, AJ, 145, 1
Bouchy, F., Bonomo, A. S., Santerne, A., et al. 2011, A&A, 533, A83
Bruntt, H., Bedding, T. R., Quirion, P.-O., et al. 2010a, MNRAS, 405, 1907
Chambers, J. E. 1999, MNRAS, 304, 793
Díaz, R. F., Almenara, J. M., Santerne, A., et al. 2014, MNRAS, 441, 983
Kipping, D. M. 2014, MNRAS, 440, 2164
Rowe, J. F., Bryson, S. T., Marcy, G. W., et al. 2014, ApJ, 784, 45

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