A system of three transiting super-Earths in a cool dwarf star

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ABSTRACT

We present the detection of three super-Earths transiting the cool star LP415-17, monitored by K2 mission in its 13th campaign. High resolution spectra obtained with HARPS-N/TNG showed that the star is a mid-late K dwarf. Using spectral synthesis models we infer its effective temperature, surface gravity and metallicity and subsequently determined from evolutionary models a stellar radius of 0.58 \( R_\odot \). The planets have radii of 1.8, 2.6 and 1.9 \( R_\oplus \) and orbital periods of 6.34, 13.85 and 40.72 days. High resolution images discard any significant contamination by an intervening star in the line of sight. The orbit of the furthest planet has radius of 0.18 AU, close to the inner edge of the habitable zone. The system is suitable to improve our understanding of formation and dynamical evolution of super-Earth systems in the rocky – gaseous threshold, their atmospheres, internal structure, composition and interactions with host stars.

Key words: planets and satellites: detection – techniques: photometric – techniques: spectroscopic – stars: low mass – stars: individual: LP415-17

1 INTRODUCTION

Transiting planetary systems are of great value for the characterization of exoplanetary atmospheres (Charbonneau et al. 2000; Kreidberg et al. 2014), the understanding of planetary formation and evolution (Owen et al. 1999) and for the study of the interactions with their host stars (Cauley et al. 2017). Cool dwarf stars are well suited to find Earth size and super-Earth size planets by the transit method, since transits produce deeper dimmings than in solar-type stars. The amplitude of signals in transit transmission spectroscopy is also higher for stars with small radius, favoring these type of stars for future atmospheric studies of their planetary systems (Gillon et al. 2016).

The Kepler mission (Borucki et al. 2010) has achieved a large number of detections of transiting planets (Howard et al. 2012). In its second mission (Howell et al. 2014), the satellite performs observations of different ecliptic plane fields for periods of time spanning about 80 days. Multiple signals of exoplanet candidates are present in concluded campaigns (Vanderburg et al. 2015; Crossfield et al. 2016). Campaign 13th has focused in the Hyades and Taurus region, centered in \( \alpha=04:51:11, \delta=+20:47:11 \), between 2017 March 08th and 2017 May 27th. In this campaign K2 observed 26.242 targets at standard long cadence mode and 118 targets at short cadence mode. LP415-17 (\( \alpha=04:21:52.487, \delta=+21:21:12.96 \)) has been observed in low cadence mode.

In this letter, we present the detection of three super-Earths transiting the star LP415-17 (EPIC 210897587, 2MASS 04215245+2121131). In section 2 we describe the characterization of the star from spectra acquired with HARPS-N spectrograph and the analysis of the K2 photometric time series. We also discuss possible contaminating sources and the main parameters derived for the planets. In section 3 we present estimations of the masses, discuss the
stability of the system and its suitability for future characterization by transmission spectroscopy. In section 4 we summarize the main conclusions derived from this work.

2 METHODS

2.1 Stellar characterization

We obtained three spectra, 1800 seconds of exposure time each, with HARPS-N (Cosentino et al. 2012) a fibred high resolution echelle spectrograph installed at the 3.6 m Telescopio Nazionale Galileo in the Roque de los Muchachos Observatory (Spain) with a resolving power of R = 115,000 over a spectral range from 380 to 690 nm. We have averaged them to obtain a final spectrum smoothed with 10-pixel step to improve the visualization of spectral features. We compared this spectrum with synthetic models (Allende Prieto et al. 2014) generated with ASSET (Koesterke et al. 2008), adopting Kurucz atmospheric models (Castelli & Kurucz 2003; Mészáros et al. 2012). Synthetic spectra have been broadened with a macroturbulence profile of 1.64 km/s (Fischer & Valenti 2005), with a rotation profile taking $v_{\text{rot}} = 1.8$ km/s Gray (2005) and with a gaussian profile for instrumental broadening at resolution of 115,000 (FWHM ~ 2.6 km/s). The effective temperature has been estimated using the infrared flux method (González Hernández & Bonifacio 2009). We apply $T_{\text{eff}}$ – (color, [Fe/H]) calibrations for dwarf stars, correcting for extinction the stellar magnitudes according to $A_X = R_X \times (B - V)$. $R_X$ was obtained from McCall (2004), and the reddening $E(B-V)$ from the dust maps (Schlegel et al. 1998), but corrected using the equations in Bonifacio et al. (2000) for the estimated distance to the star (82 pc) and galactic latitude. We obtained $E(B-V)=0.087$ and $T_{\text{eff}}=4258 \pm 150$ K.

The metallicity and $\log g$ have been obtained via comparison of the observed spectrum with synthetic spectra, resulting [Fe/H] $= -0.3 \pm 0.2$ and $\log g = 4.6 \pm 0.3$ (Fig. 1). We compare the stellar parameters and metallicity with a grid of tabulated isochrones (Bertelli et al. 1994), and obtain $R_{\odot} = 0.55_{-0.03}^{+0.06}$, $M_{\odot} = 0.65_{-0.02}^{+0.02}$ and $\alpha_{\odot} = 7.95_{-0.66}^{+0.34}$ mag. In Fig. 2 we compare the observed spectrum of LP415-17 with that of the well characterized star HD199981 (Kordopatis et al. 2013), whose parameters (K0V, $T_{\text{eff}} = 4263K$, $\log g = 4.97$) are very close to our results for LP415-17.

Adopting $M_V=12.54$, we estimate a distance to LP415-17 of $D=82_{-29}^{+29}$ pc. We measured a radial velocity from the HARPS-N spectrum, which combined with the proper motions reported in Table 1 results in velocity components $U=-38.2$ km/s, $V=60.4$ km/s, $W=31.8$ km/s. A comparison with the kinematic and metallicity properties of the Copenhagen Survey of the Solar neighbourhood (Nordström et al. 2004), suggests that LP 415-17 could be a member of the Hercules stream, which according to Bensby et al. (2007) could be a combination of thin and thick disk stars originating in interactions of the inner disk with the bar of our Galaxy.

From the observed spectrum we determine a $K_{\text{HI}}/K$ index of $-4.85 \pm 0.13$ which according to Suárez Mascareño et al. (2015) indicates a likely rotation period of 34.8 ± 8.2 days. Table 1 summarizes stellar parameters for LP415-17.

| Parameter | Value  |
|-----------|--------|
| $V$ [mag] | 12.806 ± 0.005 |
| $R$ [mag] | 12.286 ± 0.006 |
| $I$ [mag] | 12.289 ± 0.090 |
| $J$ [mag] | 10.274 ± 0.021 |
| $H$ [mag] | 9.686 ± 0.021 |
| $K$ [mag] | 9.496 ± 0.014 |
| $T_{\text{eff}}$ [K] | 4258 ± 150 |
| $\log g$ [cgs] | 4.6 ± 0.3 |
| $M_V$ [mag] | 7.95_{-0.66}^{+0.34} |
| $\log(\sigma/R_{\text{HI}})$ | -4.85 ± 0.13 |
| $P_{\text{rot}}$ [d] | 34.8 ± 8.2 |
| Distance [pc] | 82_{-29}^{+29} |
| $V_r$ [km/s] | 19.1 ± 0.3 |
| $\mu_{\alpha}$ [mas/yr] | 201.9 ± 6.9 |
| $\mu_{\delta}$ [mas/yr] | -71.3 ± 4.3 |
| U, V, W [km/s] | -38.2, -69.4, 31.8 |

2.2 K2 photometric data

The light curve of LP415-17 exhibits clear signals of at least three transiting objects (Fig. 3). We analyzed the K2 corrected photometry from the star following the work of Vanderburg & Johnson (2014), applying a spline fit to trend stellar variability and search for periodic signals with a Box Least Squares (BLS) method (Kovács et al. 2002) on flattened data. Once BLS finds a transit signal, it is fitted, removed and another search for transit signals is performed. Following this method, we find three transit signals of planet candidates with orbital periods 6.342 ± 0.002 days (b), 13.850 ± 0.006 days (c) and 40.718 ± 0.005 days (d).

To estimate the main parameters for each planet we analyzed each phase-folded transit using MCMC, fitting models from Mandel & Agol (2002) with the EXOFAST package (Eastman et al. 2013), resampling the light curve 10 times uniformly spaced over the 29.4 minutes for each data point and averaging (Kipping 2010) (Fig. 4). We set priors on host star ($T_{\text{eff}}=4258K$, $\log g = 4.6$, [Fe/H]=-0.3), orbital periods ($P_{\text{orb}} = 36.4$ (b), 13.85 (c), 40.72 (d)) days. Due to tidal circularization, $e=0$ for planet b. We also assume $e=0$ for c and d, for being transiting planets in multi planetary systems (Van Eylen & Albrecht 2015). The parameters obtained for planets b, c and d are summarized in Table 2.

Planet d only shows two transits in the K2 13th campaign observation window. Separate analysis of these two transits reveals coincident transit parameters, supporting the idea that this signal is created by the same object. The parameters for each observed transit of planet d are summarized in Table 2.

The planets have estimated radii $1.8^{+0.2}_{-0.1}$ $R_{\oplus}$ (b), $2.6^{+0.7}_{-0.2}$ $R_{\oplus}$ (c) and $1.9^{+0.7}_{-0.2}$ $R_{\oplus}$ (d), orbital periods 6.342 ± 0.002 days (b), 13.850 ± 0.006 days (c) and 40.718 ± 0.005 days (d), and semimajor axis 0.0562_{-0.0017}^{+0.0009} AU (b), 0.0946_{-0.0030}^{+0.0031} AU (c) and 0.1937_{-0.0059}^{+0.0064} AU (d).
Figure 1. Synthetic spectral models centered in the magnesium triplet (left) and Na D doublet (right), calculated with $T_{\text{eff}}=4250$ K, [Fe/H]=-0.3 and $\log g=3.4$ (top), $\log g=4.6$ (middle) and $\log g=4.0$ (bottom), compared with the observed spectrum. The best fit is obtained with $\log g=4.6$.

Figure 2. Spectrum of LP415-17 compared with the observed spectrum of HD 199981.

2.3 False positives analysis

To exclude false positives from possible companions, we analyzed speckle images of the star at 562 and 832 nm, obtained with NESSI at the 3.5 meters WIYN telescope (Kitt peak, Arizona), available at ExoFOP–K2 \(^1\) \(^2\). Images exclude companions at 0.2 arcseconds with $\delta$mag < 3.5 and at 1 arcsecond with $\delta$mag < 6. We searched for possible contaminating background sources in images from POSS-I (Minkowski & Abell 1963) (year 1953) and 2MASS (Cutri et al. 2003) (year 1998). LP415-17 exhibits high proper motion $\mu_{\alpha}$=201.9 mas/year $\mu_{\delta}$=−71.3 mas/year so we can inspect for background sources at LP415-17’s position during the K2 13\(^{th}\) campaign. No background object is found at the current star position (Fig. 5).

Specule images from WIYN, inspection of POSS-I and

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1 https://exofop.ipac.caltech.edu/k2/
2 Images where taken by Hirano et al. (2018). We noticed their work in this system during the revision process.


2MASS images, statistical analysis performed with vespa package (Morton 2012, 2015) (obtaining FPP < 10^{-5} for all the planets) and taking into account FPP overestimation for multi planet systems (Lissauer et al. 2011; Sinukoff et al. 2016), make us to reject possible contaminating sources, concluding that the transit signals in LP 415-17 are of planetary origin.

3 DISCUSSION

Following the mass – radius relation (Weiss & Marcy 2014)

\[ \frac{M_p}{M_\oplus} = 2.69 \times \left( \frac{R_p}{R_\oplus} \right)^{0.93} \]

for planets satisfying 1.5 \leq R_p/R_\oplus \leq 4, we obtain

\[ M_b=4.7 \ M_\oplus, \ M_c=6.5 \ M_\oplus, \ M_d=4.9 \ M_\oplus \] for planets b, c, and d, respectively. Assuming M_p \ll M_* , circular orbits and sin i \sim 1, we compute induced amplitudes in stellar velocity variations of 2.2 m/s for planet b, 2.3 m/s for planet c and 1.2 m/s for planet d.

Given the visual magnitude of the star (V=12.8) the required radial velocity monitoring at 1 m/s precision is hard to obtain for HARPS-like spectrographs in medium size telescopes, however is well suited for ESPRESSO (Pepe et al. 2014; González Hernández et al. 2017) at the VLT. The moderated chromospheric activity of the star is likely to induce RV signals of order less than 3 m/s (Suárez Mascareño et al. 2017) which should not prevent the detection of the dynamical signals induced by the planets and the determination of their masses and densities. We estimate the incident flux for planet d as F_p=2.63 F_\oplus. Habitable zone estimations (Kane et al. 2016) place the inner edge of the habitable zone at 1.5 F_\oplus, so planets b, c and d are closer to the star than the inner part of the habitable zone.

The amplitude of the signal in transit transmission spectroscopy can be estimated as R_p/h_\text{eff} (Gillon et al. 2016) with h_\text{eff} the effective atmospheric height, wich is related to the atmospheric scale height H = K T / \mu g (K Boltzmann’s constant, T atmospheric temperature, \mu atmospheric mean molecular mass, g surface gravity). We adopt h_\text{eff} = 7 H (Miller-Ricci & Fortney 2010) for a transparent volatile dominated atmosphere (\mu = 20) with 0.3 Bond albedo. With these assumptions we estimate the amplitudes of transit transmission spectroscopy signals as 2.2 \times 10^{-5} (b), 3.5 \times 10^{-5} (c) and 1.2 \times 10^{-5} (d).

We tested the stability of the system simulating its evolution for 10^6 years with the Mercury package (Chambers 1999), using Bulirsch – Stoer integrator, adopting circular orbits and masses from the mass - radius relation. Our simulations show no significant changes in the eccentricity (always below 0.0005 for all the planets) or in the inclination of the orbits (always below 1.6^\circ, 1.2^\circ and 1^\circ for planets b, c and d), pointing toward a dynamically stable system.

4 CONCLUSIONS

We presented a system with three transiting super-Earths orbiting a mid-late type K-dwarf star, discovered with photometric data from K2. The star has been studied and characterized in detail, analyzing its spectrum and long time photometric series. The detected planets have radii 1.8^{+0.2}_{-0.1} \ R_\oplus (b), 2.6^{+0.7}_{-0.2} \ R_\oplus (c), 1.9^{+0.7}_{-0.2} \ R_\oplus (c) and orbital periods 6.34\pm0.002 \text{ days} (b), 13.85\pm0.006 \text{ days} (c), 40.71\pm0.005 \text{ days} (d). Additional photometric monitoring is required to confirm planet d and radial velocity monitoring with ultra-stable spectrographs at 8-10 m telescopes is necessary to determine accurate planetary masses.

The amplitudes of atmospheric signals in transmission spectroscopy have been estimated at \sim 20 ppm, making the system a good target to incoming facilities such as James Webb Telescope.
A system of three transiting super-Earths in a cool dwarf star

Table 2. Parameters for planets b, c and d.

| Planet Parameters | b | c | d |
|-------------------|---|---|---|
| Orbital period (P) [d] | 6.342±0.002 | 13.850±0.006 | 40.718±0.005 |
| Semi-major axis (a) [AU] | 0.056±0.0013 | 0.0946±0.0011 | 0.193±0.0004 |
| Radius (R_p) [R_⊕] | 1.8±0.2 | 2.6±0.7 | 1.9±0.7 |
| Mass (M_p) [M_⊕] | 4.7±0.3 | 6.5±1.3 | 4.9±1.7 |
| Equilibrium Temperature (T_eq) [K] | 708±36 | 583±35 | 381±57 |
| Transit Parameters | b | c | d |
| Impact Parameter (b) | 2992.068±0.002 | 2995.426±0.003 | 2990.500±0.003 |
| Semi-major axis in stellar radii (R_p/R_*) | 0.028±0.001 | 0.021±0.0006 | 0.027±0.0001 |
| Linear limb-darkening coeff (u1) | 0.644±0.063 | 0.614±0.068 | 0.597±0.065 |
| Quadratic limb-darkening coeff (u2) | 0.132±0.074 | 0.148±0.071 | 0.144±0.091 |
| Inclination (i) [deg] | 88.3±0.9 | 89.96±0.78 | 89.75±0.75 |
| Impact Parameter (b) | 0.34±0.24 | 0.45±0.31 | 0.33±0.08 |
| Transit depth (d) | 0.0006±0.0000 | 0.00103±0.00009 | 0.000074±0.000002 |
| Total duration (T_t) [days] | 0.005±0.0000 | 0.01470±0.0010 | 0.18607±0.00025 |
| Ingress/egress duration (r) [days] | 0.0030±0.00005 | 0.0056±0.0009 | 0.0060±0.00010 |

(1): The masses are estimated using mass-radius relation from Weiss & Marcy (2014).

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(1): The masses are estimated using mass-radius relation from Weiss & Marcy (2014).

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