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K2-295 b and K2-237 b: Two Transiting Hot Jupiters

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ABSTRACT

We report the discovery from K2 of two transiting hot Jupiter systems. K2-295 (observed in Campaign 8) is a K5 dwarf which hosts a planet slightly smaller than Jupiter, orbiting with a period of 4.0 d. We have made an independent discovery of K2-237 b (Campaign 11), which orbits an F9 dwarf every 2.2 d and has an inflated radius 60–70% larger than that of Jupiter. We use high-precision radial velocity measurements, obtained using the HARPS and FIES spectrographs, to measure the planetary masses. We find that K2-295 b has a similar mass to Saturn, while K2-237 b is a little more massive than Jupiter.

Key words: *Planetary systems – Planets and satellites: detection – Planets and satellites: individual: K2-295, K2-237*

1. Introduction

Two decades after the discovery of the first hot Jupiter, there remains much to be understood about these intrinsically rare objects (*e.g.*, Howard *et al.* 2012). Open questions concern the formation and migration of hot Jupiters, as well as the nature of the mechanism responsible for their inflation.

Most well-characterized hot Jupiter systems were discovered by wide-field, ground-based surveys such as WASP (Pollacco *et al.* 2006) and HATNet (Bakos *et al.* 2002). Recently, the K2 mission (Howell *et al.* 2014) has been used to discover such systems, and can determine planetary radii to greater precision. Ground-based radial velocity (RV) observations remain crucial, not only to confirm the planetary nature of the system, but to enable a fuller characterization by measuring the planet-to-star mass ratio. It is only by increasing the sample of hot Jupiter systems with well-measured properties that we will be able to more fully understand them.

In particular, hot Jupiters, particularly low-density or inflated planets, are attractive targets for atmospheric characterization (*e.g.*, Seager and Deming 2010, Sing *et al.* 2016). In addition, detections of evaporating atmospheres often come from this same sample (Lyman-alpha – Vidal-Madjar *et al.* 2003, H-alpha – Jensen *et al.* 2012, HeI – Spake *et al.* 2018) and represent a possible mechanism for the transformation of hot gas giants into hot rocky super-Earths (Valencia *et al.* 2010, Lopez, Fortney and Miller 2012).

In this paper we report the discovery by the KESPRINT collaboration* two transiting hot Jupiter systems, K2-295 b and K2-237 b, observed in K2 Campaigns 8 and 11, respectively. We use radial velocity follow-up measurements to confirm the planetary nature of the systems, and to measure the planetary masses. The discovery of K2-237 b was recently reported by Soto *et al.* (2018), who measured the planet's mass using RVs from the CORALIE and HARPS instruments. Here, we report an independent discovery of the same planetary system, and confirm their conclusion that the planet is inflated. We also perform a joint analysis incorporating the radial velocity data obtained by Soto *et al.* (2018).

2. Observations

2.1. K2 photometry

K2-295 was observed as part of K2's Campaign 8, from January 04 to March 23, 2016. K2-237 was observed as part of Campaign 11, which ran from September 24 to December 07, 2016. A change in the roll attitude of the spacecraft was required part way through the observing campaign. This has the effect that the C11 data are divided into two segments, with a 76-hour gap between 2016 October 18 and 21 where no observations were made[†].

We used two different detection codes to search the publicly available light curves, produced by Vanderburg and Johnson (2014), for periodic transit-like signals. EXOTRANS/VARLET (Grziwa, Pätzold and Carone 2012, Grziwa and Pätzold 2016) and DST (Cabrera *et al.* 2012) detected consistent signals for both K2-295 and K2-237. K2-295 undergoes transits of about 2% depth, approximately every 4 d, whereas the transits of K2-237 are around 1.5% deep, and repeat every 2.2 d. This system was also detected using the BLS algorithm and an optimized frequency grid, described by Ofir (2014).

We also note that K2-295 was recently reported as a planetary candidate by Petigura *et al.* (2018), who report stellar properties for this target, determined from a Keck/HIRES spectrum using SPECMATCH-EMP (Yee, Petigura and von Braun 2017). The values reported by Petigura *et al.* (2018) are in good agreement with those obtained from our independent data and analysis (see Section 3.2). Basic catalog information on K2-295 and K2-237 are given in Table 1.

2.2. High Resolution Imaging

We obtained high resolution/contrast images of K2-295 using the Infrared Camera and Spectrograph (IRCS, Kobayashi *et al.* 2000) on Subaru with the adaptive-optics system (AO188, Hayano *et al.* 2010) on UT November 7, 2016. We observed the target with the *H*-band filter and fine-sampling mode (1 pix = 0.''02057). For

*<http://www.kesprint.science>

[†]See K2 Data Release Notes at <https://keplerscience.arc.nasa.gov/k2-data-release-notes.html>

Table 1

Catalog information for K2-295 and K2-237

Parameter	K2-295	K2-237
RA [J2000.0]	01 ^h 18 ^m 26 ^s .376	16 ^h 55 ^m 04 ^s .534
Dec [J2000.0]	+06°49′00″.74	−28°42′38″.03
pmRA* [mas/yr]	54.98 ± 0.05	−8.57 ± 0.10
pmDec* [mas/yr]	−34.96 ± 0.04	−5.56 ± 0.05
parallax* [mas]	4.27 ± 0.03	3.15 ± 0.07
Magnitudes		
<i>B</i>	15.07 ± 0.08	12.19 ± 0.07
<i>g</i> '	14.55 ± 0.04	11.83 ± 0.06
<i>V</i>	13.95 ± 0.04	11.60 ± 0.05
<i>r</i> '	13.46 ± 0.03	11.45 ± 0.03
Kepler	13.54	11.47
<i>i</i> '	13.10 ± 0.06	11.31 ± 0.04
<i>J</i> (2MASS)	11.81 ± 0.03	10.51 ± 0.02
<i>H</i> (2MASS)	11.26 ± 0.02	10.27 ± 0.02
<i>K</i> (2MASS)	11.14 ± 0.03	10.22 ± 0.02
Additional identifiers:		
EPIC	220501947 (C8)	229426032 (C11)
UCAC	485-001859	307-097169
2MASS	01182635+0649004	16550453-2842380

*Data taken from Gaia DR2.

K2-295, both saturated (36 s) and unsaturated (4.5 s) frames were repeatedly obtained with a five-point dithering, which were used to search for faint companions and absolute flux calibration, respectively. The total scientific exposure amounted to 540 s for the saturated frames.

We observed K2-237 with the Multi-color Simultaneous Camera for studying Atmospheres of Transiting exoplanets (MuSCAT, Narita *et al.* 2015), mounted on the 1.88-m telescope at the Okayama Astronomical Observatory. We conducted observations on UT August 7, 2017, obtaining 30 images with the exposure time of 2.5 s in the Sloan *g*' , *r*' , and *z*' bands. The pixel scale of 0.''36/pixel and median seeing of 2.''1 allow the detection of faint objects a few arcseconds away from the target star.

We also performed Lucky Imaging (LI) of K2-237 using the FastCam camera (Oscos *et al.* 2008) on the 1.55-meter Telescopio Carlos Sánchez (TCS) at Observatorio del Teide, Tenerife. FastCam is a very low noise and fast readout speed EMCCD camera with 512 × 512 pixels (with a physical pixel size of 16 microns, and a FoV of 21.''2 × 21.''2). During the night of July 19, 2017 (UT), 10 000 individual frames of K2-237 were collected in the Johnson-Cousins *I*-band, with an exposure time of 50 ms for each frame.

2.3. Spectroscopic Observations

We obtained a single reconnaissance spectrum of K2-295 with the Robert G. Tull coude spectrograph (Tull *et al.* 1995) on the 2.7-m Harlan J. Smith Telescope at McDonald Observatory, Texas. The goal of the observation (before the availability of Gaia DR2) was to check that the target is not an SB2, a giant star, or a fast rotator, in which cases it is likely to be a false positive, or unamenable to radial velocity follow-up observations. The observation was conducted on October 13, 2016, and the exposure time was 1611 s, yielding $S/N = 35$ per resolution element at 565 nm.

Table 2
Radial velocity measurements

BJD _{TDB} -2450000	RV [km/s]	σ_{RV} [km/s]	BIS [km/s]	σ_{BIS} [km/s]	Inst. ^a
K2-295					
7668.668055	-16.569	0.017	0.028	0.034	FIES
7669.555227	-16.657	0.012	0.035	0.024	FIES
7682.549665	-16.656	0.018	0.052	0.036	FIES
7684.536591	-16.576	0.019	0.034	0.038	FIES
<i>7717.374193</i>	<i>-16.610</i>	<i>0.012</i>	<i>0.040</i>	<i>0.024</i>	<i>FIES</i>
7769.395395	-16.612	0.020	0.025	0.040	FIES
7777.384377	-16.584	0.018	0.022	0.036	FIES
K2-237					
7954.463961	-22.354	0.027	0.022	0.054	FIES
7955.456791	-22.641	0.061	-0.086	0.122	FIES
7956.432724	-22.463	0.053	0.040	0.106	FIES
7964.393400	-22.707	0.067	0.086	0.134	FIES
7965.402076	-22.354	0.045	0.003	0.090	FIES
7966.393358	-22.625	0.042	-0.088	0.084	FIES
7980.391270	-22.496	0.068	0.012	0.136	FIES
<i>7981.389387</i>	<i>-22.562</i>	<i>0.050</i>	<i>-0.022</i>	<i>0.100</i>	<i>FIES</i>
7982.387408	-22.505	0.058	0.025	0.116	FIES
7983.391266	-22.353	0.066	0.004	0.132	FIES
7984.556027	-22.362	0.011	-0.019	0.022	HARPS
7985.483048	-22.213	0.016	-0.046	0.032	HARPS
7986.559244	-22.433	0.022	0.056	0.044	HARPS
7987.509317	-22.164	0.015	-0.038	0.030	HARPS
7990.472080	-22.480	0.015	0.098	0.030	HARPS
7991.487944	-22.208	0.012	-0.083	0.024	HARPS
7992.484469	-22.426	0.009	-0.029	0.018	HARPS

^aEntries in italics were taken during transit, and excluded from the modeling (see Section 5.3).

Radial velocity (RV) observations were performed using the Fibre-fed Échelle Spectrograph (FIES, Frandsen and Lindberg 1999, Telting *et al.* 2014) mounted at the 2.56-m Nordic Optical Telescope (NOT) of Roque de los Muchachos Observatory (La Palma, Spain). We employed the med-res fibre for K2-295 and the high-res fibre for K2-237, resulting in resolving powers, $R = \lambda/\Delta\lambda \approx 47\,000$ and $67\,000$, respectively. We took three consecutive exposures of 900–1200 s per observation epoch to remove cosmic ray hits. We traced the intra-exposure RV drift of the instrument by acquiring long-exposed (≈ 40 s) ThAr spectra immediately before and after the target observations (Gandolfi *et al.* 2015). The data were reduced using standard IRAF and IDL routines, which include bias subtraction, flat fielding, order tracing and extraction, and wavelength calibration. The RV measurements of K2-295 and K2-237 were extracted *via* multi-order cross-correlations with a FIES spectrum of the RV standard stars HD 190007 and HD 168009, respectively. Seven measurements of K2-295 were secured between October 2006 and January 2017 under the observing programs 54-027 and 54-205. Ten FIES spectra of K2-237 were gathered between July and August 2017 as part of the observing programs 55-019 and OPTICON 17A/064.

Additionally, we acquired seven high-resolution spectra ($R \approx 115\,000$) of K2-237 with the HARPS spectrograph (Mayor *et al.* 2003) and the ESO 3.6-m telescope at La Silla Observatory (Chile). The observations were performed in August 2017 as part of the ESO programme 099.C-0491. We set the exposure time to 900–1800 s and used the second fibre to monitor the sky background. We reduced the data with the on-line HARPS pipeline and extracted the RVs by cross-correlating the HARPS spectra with a G2 numerical mask (Baranne *et al.* 1996, Pepe *et al.* 2002).

All of our RV measurements are listed in Table 2 along with their 1σ uncertainties and the bisector spans of the cross-correlation functions.

3. Stellar Characterization

3.1. Method

We adopt the following procedure to derive masses and radii for our two host stars. In each case, we analyze a single co-added spectrum using SPECMATCH-EMP (Yee, Petigura and von Braun 2017), to determine the stellar effective temperature, T_{eff} , the stellar radius, R_* , the stellar metallicity, $[\text{Fe}/\text{H}]$, and the stellar surface gravity, $\log g$. SPECMATCH-EMP compares a stellar spectrum to spectra from a library of well-characterized stars. This stellar library contains 404 stars ranging from F1 to M5 in spectral type, which have high-resolution ($R \approx 60\,000$) Keck/HIRES spectra, as well as properties derived from other observations (interferometry, asteroseismology, spectrophotometry) and from LTE spectral synthesis.

The uncertainties on the radii from SPECMATCH-EMP are relatively large, particularly in the case of the hotter K2-237. We therefore instead choose to use the T_{eff} and $[\text{Fe}/\text{H}]$ values from SPECMATCH-EMP, and the stellar density, ρ_* , deter-

Table 3
Adopted stellar parameters

Parameter	K2-295	K2-237
T_{eff} [K]	4444 ± 70	6099 ± 110
R_* [R_{\odot}]	0.70 ± 0.02	1.38 ± 0.04
[Fe/H] [dex]	0.14 ± 0.12	0.00 ± 0.08
M_* [M_{\odot}]	0.74 ± 0.04	1.23 ± 0.05
$v \sin i$ [km/s]	2.2 ± 0.3	12 ± 1
$\log g$ [cgs]	4.63 ± 0.12	4.27 ± 0.12
Distance [pc]	225.7 ± 2.4	309.5 ± 7.4
Spectral type	K5 V	F9 V

See Sections 3.2 and 3.3 for a full discussion of how these values were derived.

mined from the transit light curves (Section 5), as inputs to the empirical relations of Southworth (2011). These relations are based on 90 detached eclipsing binary systems, and can be used to compute the stellar mass and radius. The masses and radii derived in this way are reported, along with the temperatures and metallicities from SPECMATCH-EMP, in Table 3. We use Gaia parallaxes to derive stellar radii as a check of the above method, but do not adopt these values, since the Gaia extinction values are unreliable at the individual-star level (Andrae *et al.* 2018).

3.2. K2-295

For K2-295, we used a co-added spectrum comprised of the seven FIES spectra. The stellar radius value from the SPECMATCH-EMP analysis is $0.72 \pm 0.07 R_{\odot}$, which is in excellent agreement with the value derived using Southworth’s empirical relations (Table 3).

A spectral analysis was also performed on the Tull reconnaissance spectrum, using KEA (Endl and Cochran 2016), yielding the following parameters: $T_{\text{eff}} = 4680 \pm 97$ K, $\log g = 4.38 \pm 0.16$ [cgs], $[\text{Fe}/\text{H}] = -0.24 \pm 0.10$ dex, and $v \sin i = 2.2 \pm 0.3$ km/s. The T_{eff} and $\log g$ values are in reasonable agreement (within 2σ) with those from SPECMATCH-EMP, although we note that the metallicity values differ by more than 2σ .

Petigura *et al.* (2018) report stellar parameters for K2-295, based on a Keck/HIRES spectrum. We find that our values are in excellent agreement with theirs ($T_{\text{eff}} = 4398 \pm 70$ K, $[\text{Fe}/\text{H}] = 0.17 \pm 0.12$ dex, and $R_* = 0.73 \pm 0.1 R_{\odot}$). Finally, we used the parallax value from the second data release of the Gaia mission (Gaia Collaboration *et al.* 2016, 2018), corrected with the systematic offset derived by Stassun and Torres (2018), along with the bolometric correction ($BC_G = -0.236 \pm 0.013$ mag) of Andrae *et al.* (2018) and our T_{eff} value to estimate the stellar radius of K2-295, assuming zero extinction. We derive a radius of $0.74 \pm 0.03 R_{\odot}$, which is in good agreement with our adopted value.

3.3. K2-237

The seven HARPS spectra of K2-237 were co-added, and analyzed using the method described above. The radius derived using SPECMATCH-EMP is $1.36 \pm 0.22 R_{\odot}$, which agrees well with our adopted value (Table 3). As a check, we also analyzed the same co-added spectrum using SME (Spectroscopy Made Easy, Valenti and Piskunov 1996, Valenti and Fischer 2005) with ATLAS 12 model spectra (Kurucz 2013) and pre-calculated atomic parameters from the VALD3 database (Ryabchikova *et al.* 2011, 2015). The microturbulent velocity was fixed to 1.3 km/s (Bruntt *et al.* 2010), and the macroturbulent velocity to 5.2 km/s (Doyle *et al.* 2014). The results of our SME analysis ($T_{\text{eff}} = 6220 \pm 120$ K, $[\text{Fe}/\text{H}] = 0.15 \pm 0.15$ dex, $\log g = 4.28 \pm 0.12$ [cgs]) are also in excellent agreement with our adopted values.

A further comparison was made to the stellar parameters available at the ExoFOP-K2 website[‡] which were generated using the methodology of Huber *et al.* (2016). These parameters have very much larger uncertainties than our parameters, but all parameters except stellar density (234 ± 267 kg/m³) agree to within 1σ . We note that the mass and radius given on ExoFOP result in a higher density of around 420 kg/m³. Using the Gaia DR2 parallax, assuming zero extinction, and $BC_G = 0.076 \pm 0.034$ mag, we find $R_* = 1.21 \pm 0.06 R_{\odot}$, which is slightly more than 2σ from our adopted value. In order to make the Gaia-derived radius match our adopted radius, we require extinction in the Gaia bandpass, $A_G = 0.29$, which is consistent with the value of $0.25_{-0.20}^{+0.15}$ reported in Gaia DR2.

We also compared our stellar parameters to those derived by Soto *et al.* (2018). The mass and radius estimates are in reasonably good agreement, with the values of Soto *et al.* (2018) around 1σ larger than ours. This is probably explained by the higher temperature found by Soto *et al.* (2018) ($T_{\text{eff}} = 6257 \pm 100$ K). Using this temperature and our stellar density as inputs to the Southworth (2011) relations, we obtain a stellar radius very close to their value ($1.42 \pm 0.04 R_{\odot}$ vs. $1.43_{-0.07}^{+0.06} R_{\odot}$). We note, however, that the stellar density implied by the Soto *et al.* (2018) mass and radius values ($\rho_* = 0.44 \pm 0.06$) is inconsistent at more than 5σ with their quoted density value ($\rho_* = 0.102_{-0.010}^{+0.012}$). In solar units, our derived stellar density (from light curve modeling) is $\rho_* = 0.47 \pm 0.03 \rho_{\odot}$. It is unclear how the density quoted by Soto *et al.* (2018) was derived.

We computed a Lomb-Scargle periodogram using the light curve further decorrelated using a polynomial fit, and with in-transit points removed. We found a peak at around 5.1 d, which we attribute to stellar rotation. The amplitude of this rotational variability varies over the course of the K2 observations, and was strongest in the first part of the light curve.

This detected period closely matches that found by Soto *et al.* (2018) (5.07 ± 0.02 d). Using their period and our stellar radius and $v \sin i$ (from SME) values, we determine the stellar inclination angle, $i_* = 59_{-7}^{+9}$ degrees. This is slightly larger

[‡]https://exofop.ipac.caltech.edu/k2/edit_target.php?id=229426032

than the $51.56^{+3.73}_{-2.80}$ degrees determined by Soto *et al.* (2018), and we also note that our 2σ error bar (59^{+31}_{-13} degrees) encompasses 90° . We would therefore caution against concluding that the stellar spin and planetary orbital axes are misaligned. Our smaller stellar radius is consistent with them being aligned or near-aligned.

3.4. Distances

The distances quoted in Table 3 are derived from the parallaxes listed in the second Gaia data release (Gaia Collaboration *et al.* 2016, 2018). They are in good agreement with distances calculated from estimates of the absolute magnitude, albeit with significantly smaller uncertainties. In particular, we note that the Gaia distance to K2-237 is consistent with that derived by Soto *et al.* (2018), but that the Gaia uncertainty is approximately 20 times smaller.

3.5. Ages

We plotted K2-295 alongside Dartmouth isochrones (Dotter *et al.* 2008) interpolated to our stellar metallicity value (Table 3) at intervals of 1 Gyr (Fig. 1, left). We determined the range of ages which are compatible with our stellar density and effective temperature from a simple visual inspection (as was used in *e.g.*, Smith *et al.* 2014). The age is poorly-constrained – the 1σ uncertainties span all ages greater than about 8.5 Gyr. We note, however, that these uncertainties are probably underestimated, since we do not account for the uncertainty on the metallicity, nor the systematic errors in the Dartmouth stellar models. The latter effect could be mitigated against by considering a variety of stellar models (as in *e.g.*, Southworth 2009), but considering the large uncertainties we opt not to do this, and instead draw no firm conclusions about the age of K2-295.

Plotting K2-237 alongside theoretical isochrones (Dotter *et al.* 2008) yields a best-fitting age of approximately 6 ± 1 Gyr (Fig. 1, right). As for K2-295, we acknowledge that the uncertainty on this age determination is probably underestimated. Using the 5.07 ± 0.02 d rotation period (Soto *et al.* 2018) as an input

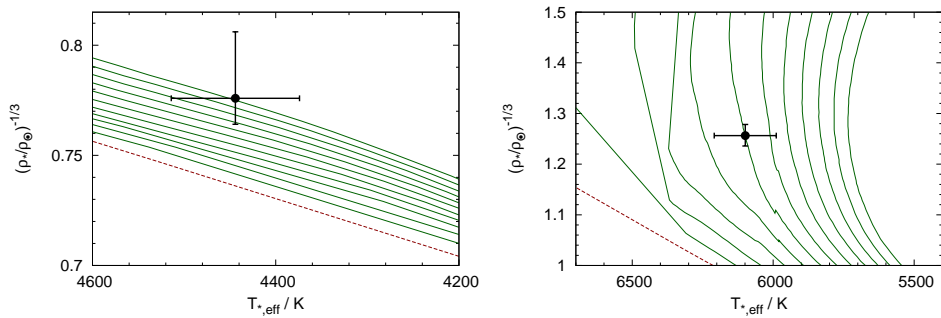


Fig. 1. Modified Hertzsprung-Russell diagrams for K2-295 (*left*) and K2-237 (*right*). In *each panel* the target star is represented with a black circle. Dartmouth isochrones (Dotter *et al.* 2008) are shown for 1.0 Gyr (dashed red line), and at 1 Gyr spacings, up to 12.0 Gyr.

to the gyrochronology relation of Barnes (2010), we derive an age for K2-237 of 1.2 ± 0.7 Gyr. We use our stellar mass value and linear interpolation of Table 1 of Barnes and Kim (2010) to determine the convection turn-over timescale. We note, however, that ages derived from isochrones and from gyrochronology often disagree for planet-host stars (Brown 2014, Maxted, Serenelli and Southworth 2015), perhaps because hot Jupiters tidally interact with their host stars, spinning them up.

3.6. Spectral Type

The spectral types listed in Table 3 were determined using the tabulation of Pecaut and Mamajek (2013). Our stellar effective temperatures were compared to those listed in the online version of their table[§].

4. Contamination from Neighboring Objects

4.1. K2-295

The Subaru/IRCS data were reduced following the procedure in Hirano *et al.* (2016), and we obtained the calibrated combined images for the saturated and unsaturated frames respectively. To estimate the achieved contrast of the saturated image, we computed the flux scatter within the annulus as a function of angular separation from the centroid of the star. Fig. 2 plots the 5σ contrast curve together with the target image with the field-of-view of $4'' \times 4''$. K2-295 is a single star to the detection limit, meaning that the light curve is free from contamination from nearby objects.

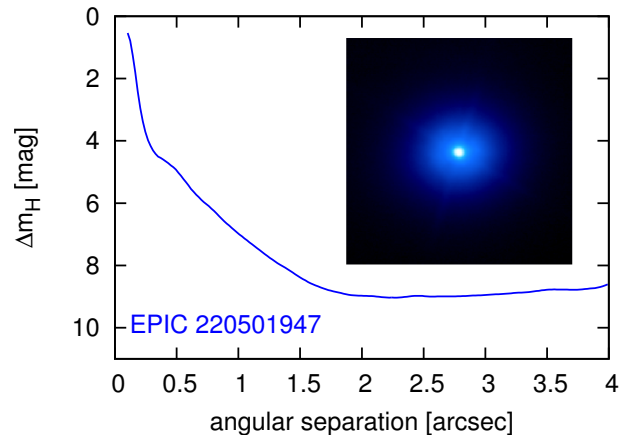


Fig. 2. Results of Subaru IRCS imaging of K2-295. The curve indicates the 5σ detection limit, as a function of angular separation, and the inset image ($4'' \times 4''$, North is up, East is left) indicates that there is no evidence for any close companions to K2-295.

[§]http://www.pas.rochester.edu/~mamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt

4.2. K2-237

The MuSCAT imaging reveals K2-237 to be in a rather crowded field, with several faint objects nearby. Using the r' band image (Fig. 3), we detected a total of ten objects fainter than the target within the photometric aperture used to generate the light curve. The total flux contribution of these objects relative to the target flux is 0.042. We adopt this value for the quantity of contaminating ‘third’ light, and conservatively estimate an uncertainty of half, *i.e.*, 0.021 – to account for measurement errors and the difference between the Kepler and r' bandpasses. The third light is accounted for in our modeling of the transit light curve (Section 5), and has the effect of changing the planet radius at approximately the 1σ level.

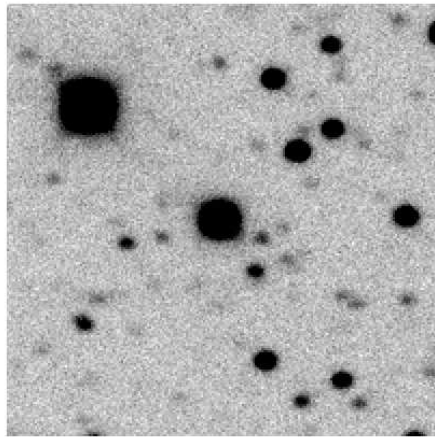


Fig. 3. MuSCAT r -band image, centered on K2-237. North is up, East is to the left, and the image is $72'' \times 72''$. A number of faint contaminating stars can be seen in the close vicinity of the target.

We constructed a high-resolution image by co-adding the best thirty per cent of the TCS/FastCam images, giving a total exposure time of 150 s. The typical Strehl ratio of these images is about 0.07. In order to construct the co-added image, each individual frame was bias-subtracted, aligned and co-added and then processed with the FastCam dedicated software developed at the Universidad Politécnica de Cartagena (Labadie *et al.* 2010, Jódar *et al.* 2013). Fig. 4 shows the contrast curve that was computed based on the scatter within the annulus as a function of angular separation from the target centroid.

Three neighboring objects were found in the image, at separations from K2-237 of between $7''$ and $11''$. The relative fluxes of these objects are consistent with those determined by MuSCAT. No bright companions were detected within $7''$ of the target (Fig. 4).

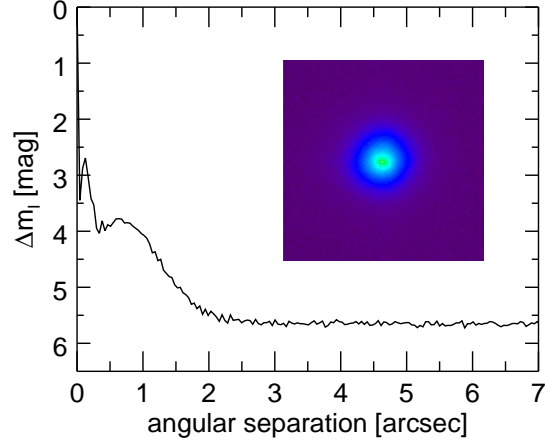


Fig. 4. *I*-band magnitude contrast curve as a function of angular separation up to $7'' 0$ from K2-237 obtained with the FastCam camera at TCS. The solid line indicates the 5σ detection limit for the primary star. The inset shows the $7'' \times 7''$ combined image of K2-237. North is up and East is left.

5. Determination of System Parameters

5.1. Light Curve Preparation

We use the EVEREST (Luger *et al.* 2016) K2 light curve for K2-295 (Fig. 5, upper panel)[¶]. For modeling the transit, we cut the light curve into pieces, selecting only those light curve points within two transit durations of the transit midtime for modeling. This makes detrending the light curve for stellar activity more straightforward, as well as reducing model computation times. This results in a series of light curve sections of length $4T_{14}$ (approximately ten hours in the case of K2-295), centered on the midpoint of each transit. Each section of the light curve is detrended using a quadratic function of time to remove the remaining signatures of stellar variability. Finally, we remove three obvious outliers from the light curve.

For K2-237, we perform the same procedure as above, but we instead use the light curve of Vanderburg and Johnson (2014) (lower panel of Fig. 5). In addition to the transits, the light curve exhibits a quasi-periodic signal which we attribute to stellar rotational variability and investigate further in Section 3.3.

5.2. The TLCM Code

We model each system using the TRANSIT AND LIGHT CURVE MODELLER (TLCM) code. TLCM has been used to model exoplanet light curves and radial velocities in numerous previous studies, including planets discovered in long-cadence K2 data (*e.g.*, K2-99b, Smith *et al.* 2017). The code is described in Csiz-

[¶]We have previously found that the EVEREST and Vanderburg and Johnson (2014) light curves are of very similar quality, with the EVEREST curves containing very slightly less noise on average. We therefore use the EVEREST light curve for K2-295. For K2-237, however, there was no EVEREST curve available when we started our modeling efforts, so we use the Vanderburg and Johnson (2014) curve instead.

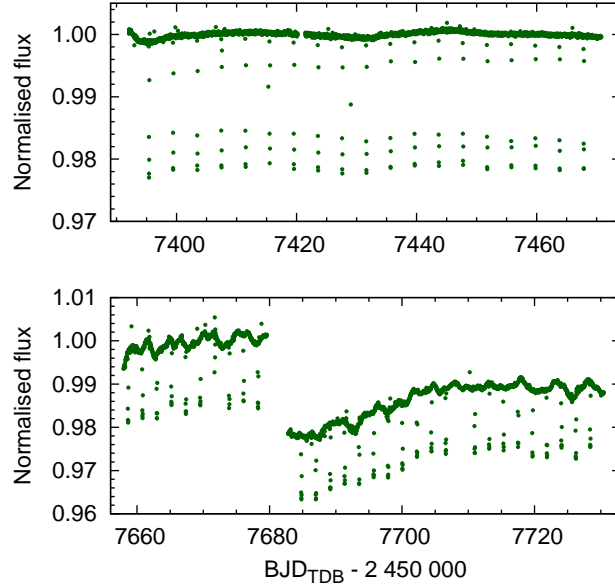


Fig. 5. K2 light curves for K2-295 (upper panel) and K2-237 (lower panel). The K2-295 light curve was produced using the EVEREST code (Luger *et al.* 2016), and the K2-237 light curve by Andrew Vanderburg (following Vanderburg and Johnson 2014). The discontinuity in the lower panel is a result of a change in the roll angle of K2 during Campaign 11 (see Section 2.1 for further details).

madia *et al.* (2015), and a more detailed description will accompany the first public release of the code (Csizmadia, under review).

In brief, TLMC fits the photometric transit using the Mandel and Agol (2002) model, compensating for K2’s long exposure times using numerical integration, and simultaneously fits a Keplerian orbit to the RV data. TLMC uses the combination of a genetic algorithm to find the approximate global minimum, followed by simulated annealing and Markov-chain Monte Carlo phases to refine the solution, and explore the neighboring parameter space for the determination of uncertainties on the model parameters.

5.3. Combined Fit

For our basic fit, we fit for the following parameters: the orbital period, P , the epoch of mid-transit, T_0 , the scaled semi-major axis (a/R_*), planet-to-stellar radius ratio (R_p/R_*), the impact parameter, b , the limb-darkening parameters, u_+ and u_- (see below), the systemic stellar RV, γ , and the RV semi-amplitude, K . In the case of K2-237, for which we have RV data from FIES and HARPS, we also fit the systematic offset between these two instruments, γ_{F-H} . For each system, one of our RV measurements was taken during transit. Since we do not model the Rossiter-McLaughlin effect, these points are not included in the modeling, and are marked in italics in Table 2.

5.4. Limb Darkening

Limb-darkening is parametrized using a quadratic model, whose coefficients, u_a and u_b are transformed to the fit parameters $u_+ = u_a + u_b$ and $u_- = u_a - u_b$. In the case of K2-237, u_+ and u_- are free parameters. For K2-295, the observational cadence of K2 is close to an integer fraction of the orbital period. This results in clumps of data points in phase space, rather than the data being evenly distributed in phase (Fig. 6). Transit ingress and egress are poorly covered, providing a weaker constraint on the limb-darkening parameters than would otherwise be the case. We therefore opt to constrain the limb-darkening parameters to take values close to (± 0.01) the theoretical values of Sing (2010) for the relevant stellar parameters and the Kepler bandpass ($u_+ = 0.7349$, $u_- = 0.5689$). We discuss this issue and related problems arising from the poor coverage of ingress and egress in an Appendix to this paper.

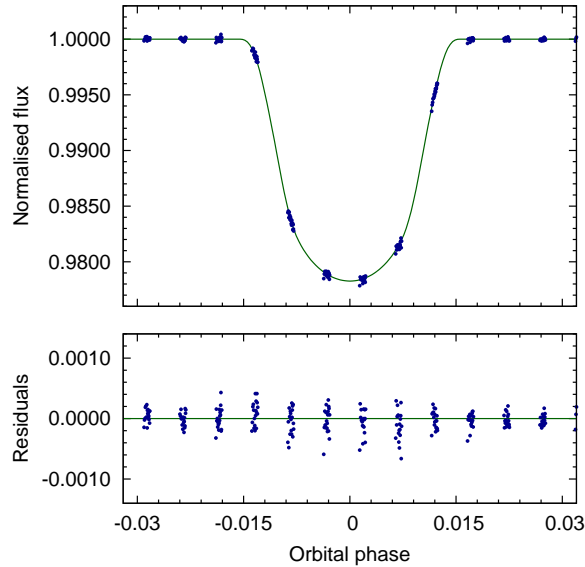


Fig. 6. Phase-folded K2 photometry (blue circles) and best-fitting model (solid green line) for K2-295, with residuals to the model shown in the *lower panel*. The light curve is that of Luger *et al.* (2016).

5.5. Orbital Eccentricity

In our basic fit, we fix the orbital eccentricity to zero, but we also used TLCDM to fit for the orbital eccentricity, e , rather than forcing a circular orbital solution. The additional parameters we fit for in this case are $e \cos \omega$ and $e \sin \omega$, where ω is the argument of periastron. We used the χ^2 values of the resulting fits to calculate the Bayesian Information Criterion (BIC) in order to establish whether the improved RV fit justifies the additional model parameters.

For both systems, we found a larger BIC value for the eccentric fit (for K2-295 $\text{BIC}_{\text{ecc}} - \text{BIC}_{e=0} = 3.6$, and for K2-237, $\text{BIC}_{\text{ecc}} - \text{BIC}_{e=0} = 5.0$). For the purposes of calculating the BIC, we considered the number of data points to be the number of RV points only, since these provide most of the information regarding orbital eccentricity. Including the photometric data points in the total would increase the BIC values, making a circular orbit even more favorable. We note that for neither system is the best-fitting eccentricity found to be significant at the 3σ level, although the eccentricity of K2-295 is poorly-constrained because of the incomplete phase coverage of the RV data. We therefore adopt $e = 0$ for both systems, as expected given both theoretical predictions for close-in exoplanetary systems, and empirical evidence that such planets only rarely exist on significantly eccentric orbits (*e.g.*, Anderson *et al.* 2012).

5.6. *RV Drift*

We also tried fitting for a linear trend in the radial velocities of each star, the presence of which can be indicative of the presence of a third body in the system. In both cases, we found that the best-fitting radial acceleration is not significant, and that the BIC clearly favors the simpler model. In summary, there is no evidence for the presence of a third body in either system.

5.7. *Checks for a Blended Binary System*

A blended eclipsing binary can mimic a transiting planetary system, but will exhibit a correlation between the RV and the RV bisector spans (Queloz *et al.* 2001). In Figs. 10 and 11, we plot these two quantities, and find that there is no such correlation in either case, as expected for true planetary systems. We note, however, that Günther *et al.* (2018) determine that the lack of a bisector correlation does not rule out all blend scenarios.

We also look for a variation of transit depth with photometric aperture size – a powerful discriminant which has been used previously to disprove previously-validated planetary candidates from K2 (Cabrera *et al.* 2017). For K2-295, we observe no change in transit depth with increasing aperture radius. For K2-237, we observe the transit depth shrink with increasing aperture radius. This is the expected behavior given that there is a nearby companion whose light dilutes the transit depth when a large photometric aperture is used. We further note that our high-resolution imaging rules out the presence of a binary companion capable of mimicking the observed transit signals, unless such a companion lies at very small ($\lesssim 1''$) sky-projected separations. Estimating the probability of such a scenario is non-trivial, requiring detailed simulations which are beyond the scope of this paper.

5.8. *Additional Photometric Signals*

We tried fitting for an occultation (centered on phase 0.5, given the evidence for circular orbits in both systems). No evidence was found for the presence of

an occultation signal in the light curve of either system. Similarly, we found no compelling evidence of any transit timing variations (TTV) in either system. Interestingly, there seems to be a variation in the transit depth of K2-237 b. This explains the higher in-transit residual scatter observed in Fig. 7, which we suggest is caused by stellar spots, which are also responsible for the rotational modulation seen in the light curve (Section 3.3).

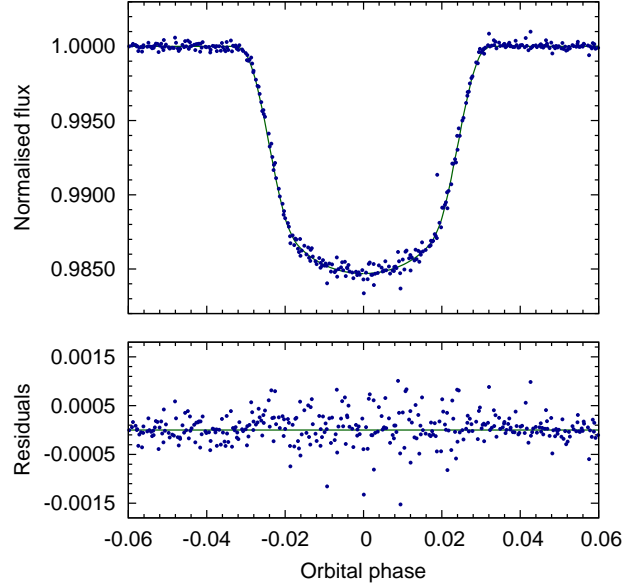


Fig. 7. Phase-folded K2 photometry (blue circles) and best-fitting model (solid green line) for K2-237, with residuals to the model shown in the *lower panel*. The light curve is that of Vanderburg and Johnson (2014).

5.9. Additional RV Data

The RV semi-amplitude and planet mass that we determine for K2-237 differ somewhat from the values ($K = 210 \pm 10$ m/s, $M_p = 1.60 \pm 0.11 M_{\text{Jup}}$) reported by Soto *et al.* (2018). We tried including their RVs (four measurements from HARPS, and nine from CORALIE) in our fit, and found that we require an offset between our HARPS measurements and theirs. We suggest that the need for this arises from the different reduction pipelines used to obtain the RVs from the HARPS spectra. Including the RVs of Soto *et al.* (2018) yields $K = 180^{+5}_{-8}$ m/s, which is compatible (at the $\approx 1\sigma$ level) with the value obtained from our data alone ($K = 168^{+5}_{-3}$ m/s, Table 4), but almost 3σ from the value of Soto *et al.* (2018). The source of this apparent discrepancy is unclear.

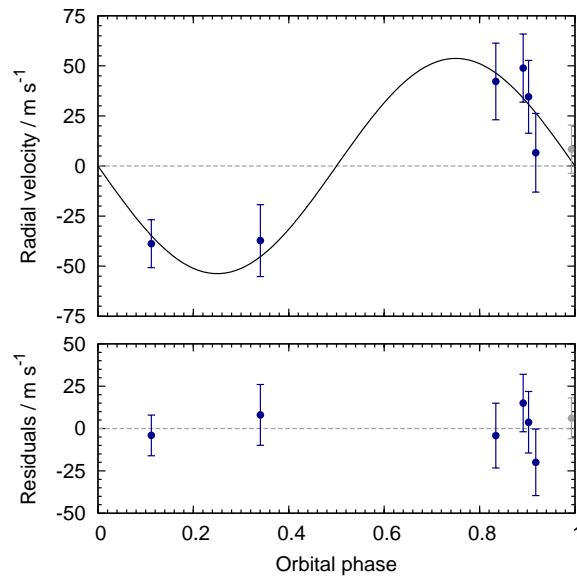


Fig. 8. Radial velocities from FIES for K2-295. The RV point taken during transit is shown in gray. Our best-fitting model is shown with a solid black line, and the residuals to the model are plotted in the *lower panel*. The data are phase-folded, and the systemic radial velocity, γ , has been subtracted.

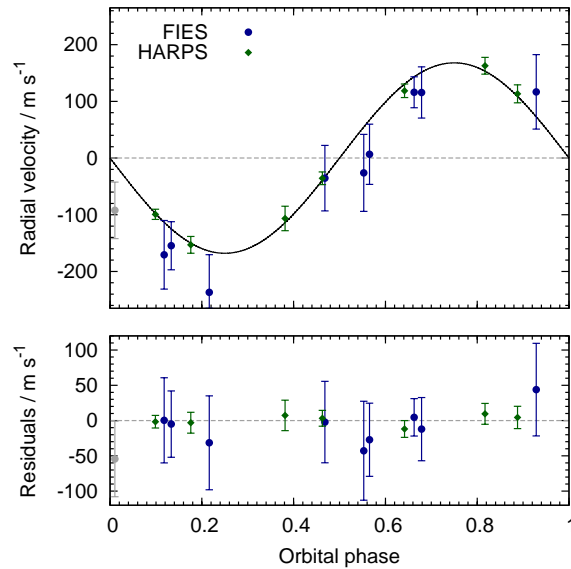


Fig. 9. Radial velocities from FIES (blue circles) and HARPS (green squares) for K2-237. The FIES RV point taken during transit is shown in gray. Our best-fitting model is shown with a solid black line, and the residuals to the model are plotted in the *lower panel*. The data are phase-folded, and the systemic radial velocity, γ , has been subtracted.

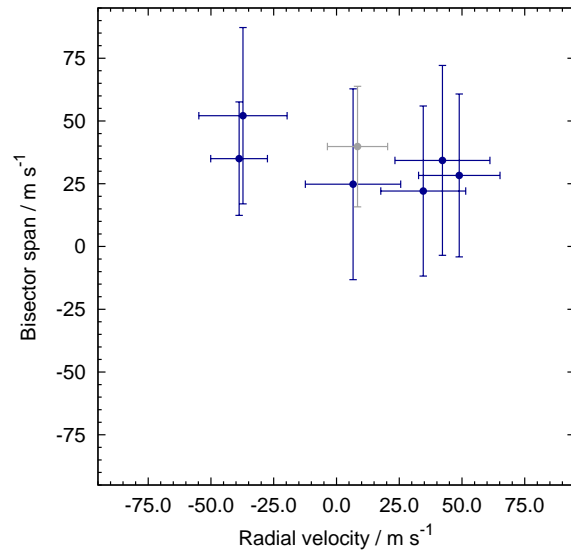


Fig. 10. Bisector span as a function of radial velocity for K2-295. As in Fig. 8, the systemic radial velocity, γ , has been subtracted. The uncertainties in the bisector spans are taken to be twice those of the radial velocities. The RV point taken during transit is shown in gray.

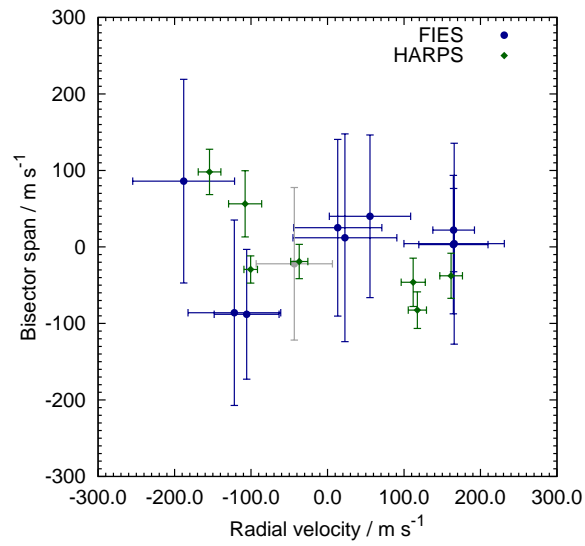


Fig. 11. Bisector span as a function of radial velocity for K2-237. As in Fig. 9, the systemic radial velocity, γ , has been subtracted, as has the fitted RV offset between the FIES and HARPS instruments, $\gamma_{\text{F-H}}$. The uncertainties in the bisector spans are taken to be twice those of the radial velocities.

Table 4
System parameters from TLCM modeling

Parameter	Symbol	K2-295	K2-237
TLCM fitted parameters:			
Orbital period	P [d]	4.024867 ± 0.000015	2.1805577 ± 0.0000057
Epoch of mid-transit	T_0 [BJD _{TDB}]	$2457395.4140498 \pm 0.0000012$	$2457656.4633789 \pm 0.0000048$
Scaled orbital major semi-axis	a/R_*	$13.76^{+0.19}_{-0.44}$	$5.503^{+0.015}_{-0.207}$
Ratio of planetary to stellar radii	R_p/R_*	$0.1304^{+0.0014}_{-0.0007}$	$0.1195^{+0.0015}_{-0.0005}$
Transit impact parameter	b	$0.17^{+0.14}_{-0.11}$	$0.520^{+0.057}_{-0.002}$
Limb-darkening parameters	u_+	$0.734 \pm 0.007^*$	$0.603^{+0.068}_{-0.062}$
	u_-	$0.569 \pm 0.007^*$	$0.02^{+0.11}_{-0.20}$
Stellar orbital velocity semi-amplitude	K [m/s]	54 ± 10	$167.9^{+4.7}_{-3.1}$
Systemic radial velocity	γ [km/s]	-16.6185 ± 0.0067	$-22.4700^{+0.0004}_{-0.0147}$
Velocity offset between FIES and HARPS	γ_{F-H} [m/s]	–	143^{+15}_{-9}
Derived parameters:			
Orbital eccentricity (adopted)	e	0	0
Stellar density	ρ_* [kg/m ³]	3043^{+128}_{-280}	663 ± 40
Planet mass	M_p [M _{Jup}]	0.335 ± 0.062	1.236 ± 0.044
Planet radius	R_p [R _{Jup}]	$0.897^{+0.011}_{-0.005}$	1.642 ± 0.050
Planet density	ρ_p [kg/m ³]	612 ± 115	370 ± 36
Orbital major semi-axis	a [au]	$0.0451^{+0.0006}_{-0.0014}$	0.0353 ± 0.0012
Orbital inclination angle	i_p [°]	$89.30^{+0.46}_{-0.62}$	84.6 ± 0.3
Transit duration	T_{14} [d]	$0.1041^{+0.0011}_{-0.0007}$	0.1251 ± 0.0032
Planet equilibrium temperature [†]	$T_{p,eq,A=0}$ [K]	852^{+14}_{-6}	1838 ± 38

*For K2-295, the limb-darkening coefficients are not freely fitted - see Section 5.4 for details.

†The equilibrium temperature is calculated assuming a planetary albedo of zero, and isotropic re-radiation.

6. Conclusions

In summary, we find that the planet orbiting the K5 dwarf K2-295 in an approximately 4-d orbit is slightly larger and more massive than Saturn ($1.06 \pm 0.01 R_{\text{Sat}}$ and $1.12 \pm 0.21 M_{\text{Sat}}$). The planetary parameters (transit duration, impact parameter, and planetary radius) reported in the planet candidate list of Petigura *et al.* (2018) are in good agreement with those derived in our analysis. The radius of K2-295 b seems to be fairly typical for a hot Saturn, slightly smaller than the similar HATS-6 b and WASP-83 b (Hartman *et al.* 2015, Hellier *et al.* 2015), but significantly larger than that of the anomalously dense HD 149026 b (Sato *et al.* 2005), which is thought to be extremely metal-rich (Speigel, Fortney and Sotin 2014).

We confirm the conclusion of Soto *et al.* (2018), that K2-237 b is significantly inflated. We find that the planet is typical of an inflated hot Jupiter – slightly more massive than Jupiter, but with a radius some 60 to 70 per cent larger than the largest planet in the Solar System. The planet orbits an F8 dwarf star.

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This research has made use of NASA’s Astrophysics Data System, the SIMBAD data base, operated at CDS, Strasbourg, France, the Exoplanet Orbit Database and the Exoplanet Data Explorer at exoplanets.org, and the Exoplanets Encyclopaedia at exoplanet.eu. We also used Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration *et al.* 2013).

This work has made use of data from the European Space Agency (ESA) mission Gaia (<https://www.cosmos.esa.int/gaia>), processed by the Gaia Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/>

consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

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Appendix

Issues Arising from the Poorly-Sampled Light Curve of K2-295

As we mentioned in Section 5.4, and can be clearly seen in Fig. 6, the K2 light curve of K2-295 is poorly-sampled in orbital phase. This is a result of the near-commensurability of the orbital period and the observational cadence. In this particular case, this leads to difficulty in determining the transit duration, and the physical parameters dependent on this.

The transit depth (and hence planet-to-star radius ratio) is well constrained by the data. There exists photometry close to the transit midpoint, and there is no problem in determining the out-of-transit baseline. However, there is no data covering any of the four contact points (the beginning and end of the ingress and egress phases). This results in little constraint on the duration of both the transit and of ingress and egress.

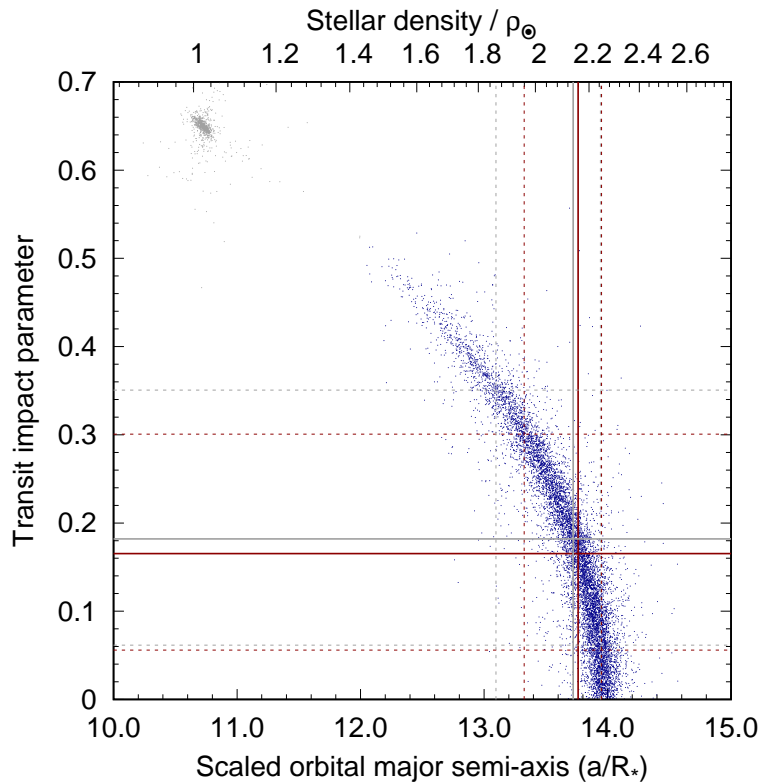


Fig. 12. Posterior distribution of impact parameter and a/R_* , when the limb-darkening coefficients are constrained as described in the text. The corresponding stellar density is indicated along the top of the plot. A total of 10 000 randomly-selected samples from the posterior distribution are shown, with excluded points colored gray. The red solid line indicates our adopted solution (median of remaining points), and the red dashed lines the 1σ confidence interval. The solid and dashed gray lines indicate the solution obtained without excluding the gray points in the *top left*.

After fitting for the limb-darkening parameters as usual, we tried fixing them to the theoretical values of Sing (2010). We took the values corresponding to $\log g = 4.5$, $[\text{Fe}/\text{H}] = 0.1$, and $T_{\text{eff}} = 4500$ K. We allow these values to vary slightly (± 0.01), to account for the uncertainty in the stellar parameters, and for the fact that the coefficients are tabulated only for certain values of $\log g$, $[\text{Fe}/\text{H}]$, and T_{eff} . The allowed variation encompasses the limb-darkening parameters tabulated for neighboring values of these parameters.

Our fits resulted in two families of solutions, revealing a degeneracy between a/R_* , b , and the limb-darkening coefficients. The two groups of solutions result in light curve fits which look nearly identical, but which have significantly different values of a/R_* , resulting in drastically different stellar densities. Instead of $a/R_* \approx 13.8$ and $b \approx 0.2$, the second solution has $a/R_* \approx 10.7$, $b \approx 0.65$, and limb-darkening coefficients that lie far from any tabulated values ($u_+ = 1.7$, $u_- = -0.3$). The resulting stellar density ($\approx 1400 \text{ kg/m}^3$) is inconsistent with our various stellar analyses (Section 3.2). Furthermore, adopting this less-dense value results in the star lying in a region of parameter space not covered by any of the Dartmouth isochrones (Dotter *et al.* 2008).

We find that even when constraining the limb-darkening coefficients, a small fraction of the MCMC posterior distribution lies in a distinct region of parameter space, with a stellar density far too low to be compatible with our knowledge of the star (Fig. 12). We therefore opt both to constrain the limb-darkening coefficients and to exclude solutions with $a/R_* < 12$ from the posterior distribution. This is illustrated in Fig. 12.

We note that previous studies have recommended fitting, rather than fixing limb-darkening coefficients, in order to avoid biasing the determination of the system parameters (Csizmadia *et al.* 2013, Espinoza and Jordán 2015). These studies did not consider poorly-sampled light curves such as that of K2-295, however. Fortunately, K2-295 lies in a region of parameter space where there is minimal difference between various tabulated limb-darkening coefficients. This is not true for all spectral types (Fig. 1 of Csizmadia *et al.* 2013).