Eclipsing binaries and fast rotators in the *Kepler* sample

Characterization via radial velocity analysis from Calar Alto^{★,★★}

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ABSTRACT

Context. The *Kepler* mission has searched for planetary transits in more than two hundred thousand stars by obtaining very accurate photometric data over a long period of time. Among the thousands of detected candidates, the planetary nature of around 15% has been established or validated by different techniques. But additional data are needed to characterize the rest of the candidates and reject other possible configurations.

Aims. We started a follow-up program to validate, confirm, and characterize some of the planet candidates. In this paper we present the radial velocity analysis of those that present large variations, which are compatible with being eclipsing binaries. We also study those showing high rotational velocities, which prevents us from reaching the necessary precision to detect planetary-like objects.

Methods. We present new radial velocity results for 13 *Kepler* objects of interest (KOIs) obtained with the CAFE spectrograph at the Calar Alto Observatory and analyze their high-spatial resolution (lucky) images obtained with AstraLux and the *Kepler* light curves of some interesting cases.

Results. We have found five spectroscopic and eclipsing binaries (group A). Among them, the case of KOI-3853 is of particular interest. This system is a new example of the so-called *heartbeat stars*, showing dynamic tidal distortions in the *Kepler* light curve. We have also detected duration and depth variations of the eclipse. We suggest possible scenarios to explain such an effect, including the presence of a third substellar body possibly detected in our radial velocity analysis. We also provide upper mass limits to the transiting companions of six other KOIs with high rotational velocities (group B). This property prevents the radial velocity method from achieving the necessary precision to detect planetary-like masses. Finally, we analyze the large radial velocity variations of two other KOIs, which are incompatible with the presence of planetary-mass objects (group C). These objects are likely to be stellar binaries. However, a longer timespan is needed to complete their characterization.

Key words. techniques: radial velocities – planets and satellites: general – binaries: eclipsing – binaries: close

1. Introduction

The need for ground-based follow-up observations of the planet candidates provided by the *Kepler* mission (Borucki et al. 2010) was known even prior to its launch on March 2009. This need comes from two sides. First, high spatial resolution is required owing to the large pixel size (~ 4 arcsec) and the typical photometric apertures (6–10 arcsec) used by *Kepler*, which permits the contamination of the light curves by close sources, mimicking planet-like transits. Second, radial velocity (RV) observations of the isolated candidates are crucial to identifying or rejecting their planetary nature. The community follow-up observing program (CFOP¹) serves as a communication tool between the different international groups working on this. The

false positive rate in the *Kepler* sample of planet candidates has been investigated by several authors (e.g., Morton & Johnson 2011; Santerne et al. 2012; Fressin et al. 2013; Coughlin et al. 2014), and more than 3000 *Kepler* objects of interest (KOIs) have been rejected so far by different groups using different techniques².

In 2011, we started a ground-based follow-up program with both high-resolution (lucky) imaging with AstraLux (Lillo-Box et al. 2012, 2014a) to detect possible close companions and high-resolution spectroscopy with CAFE³ (Aceituno et al. 2013) to characterize some of the *Kepler* candidates via RV studies, with both instruments installed at the 2.2 m telescope in the Calar Alto Observatory.

In this paper, we present the results of part of our high-resolution spectroscopic survey of isolated planet candidates in the *Kepler* sample. This survey has already confirmed the

[★] Based on observations collected at the German-Spanish Astronomical Center, Calar Alto, jointly operated by the Max-Planck Institut für Astronomie (Heidelberg) and the Instituto de Astrofísica de Andalucía (IAA-CSIC, Granada).

^{★★} Appendix A is available in electronic form at <http://www.aanda.org>

¹ <https://cfop.ipac.caltech.edu/home/>

² According to the CFOP and the NASA Exoplanet Archive (<http://exoplanetarchive.ipac.caltech.edu>, Akesson et al. 2013), among the 7348 identified KOIs to date, 3170 have been labeled as “false positives”.

³ Calar Alto Fiber-fed Echelle spectrograph.

planetary nature of Kepler-91b (KOI-2133b, Lillo-Box et al. 2014b), Kepler-432b (KOI-1299b, Ciceri et al. 2015), and Kepler-447b (KOI-1800b, Lillo-Box et al. 2015); and has detected the secondary eclipse of WASP-10b (Cruz et al. 2015). In the present paper, we analyze 13 specific candidates in our sample that have shown either large RV variations or broadened spectra owing to the fast rotation of the host stars. Among the studied candidates, we have found an eclipsing binary that shows heartbeat-like modulations on its light curve. This effect was explained and explored by Kumar et al. (1995) and is due to tidal distortions in eccentric binary systems. The first object discovered whose light curve is mainly dominated by this type of modulation was KOI-54 (Welsh et al. 2011). Since then, only a few more cases have been discovered (e.g., Thompson et al. 2012), but more cases are needed to understand and test theoretical models of how pulsations are induced from the dynamic tidal distortion. Interestingly, the RV analysis of KOI-3853 also shows indications of a possible third companion.

This paper is organized as follows. In Sect. 2.3, we describe the observations used in this analysis. Section 3 shows the analysis and results of the RV data for the found undiluted binaries (Sect. 3.1). Also, we set upper limit masses for the companions of a few fast rotators (Sect. 3.2) and study two still unsolved cases with current data in Sect. 3.3. In Sect. 4 we show the detection of peculiar (not yet reported) features in the light curves of some of the targets analyzed in this paper. Finally, a brief discussion and conclusions of these findings is provided in Sect. 5.

2. Observations

2.1. Kepler photometry

The objects analyzed in the present paper were first classified by the *Kepler* mission as potential planet hosts by the detection of planetary-like transits. We used the long cadence data of quarters Q1-Q17 of the *Kepler* mission to analyze the light curves (LCs) of some of these *Kepler* KOIs. The data were obtained from the Mikuski Archive for Space Telescopes⁴ (MAST) database. We used the Pre-search Data Conditioning Simple Aperture Photometry flux (PDCSAP, Smith et al. 2012; Stumpe et al. 2012) and detrended these data by using simple spline fitting to every set of data without jumps longer than one day. We used one-day averaged flux bins as nodes for the spline fitting. In specified cases (such in KOI-3853), we removed some parts of the light curve in the calculation of the nodes in order not to smooth or even eliminate non artificial modulations (such as primary transits, eclipses, or other real variations).

2.2. High-spatial resolution images

The presence of undiluted sources can contaminate both the *Kepler* light curve and the spectra of the target, introducing imprints that could mask or mimic a planetary signal or contaminate the determination of its properties (e.g., Daemgen et al. 2009; Adams et al. 2012; Law et al. 2014). Thus, prior to the RV observations, we obtained high-resolution images for the targets by using the lucky-imaging technique with the AstraLux instrument at the 2.2m telescope in Calar Alto. In Lillo-Box et al. (2012, 2014c), we already published the results of our high-spatial resolution survey of the *Kepler* candidates and provided details on the reduction and analysis of the data. More

Table 1. Ancillary data and calculated BSC (blended source confidence) values for the KOIs studied in this paper.

KOI	High-Res Im. ^a Ref.	Comp. (<6'')	Sep. arcsec.	Δm mag (band)	BSC %
Group A – Eclipsing binaries					
340.01	L13	0 ^b			99.99
371.01	L13	0 ^b			96.0
686.01	LB14	0			99.9
3725.01	LB14	0			99.7
3853.01	LB14	0			99.6
Group B – Fast rotators					
12.01	LB14	0			99.3
131.01	LB12	1	5.54''	3.48 (<i>i</i> _{SDSS})	–
366.01	LB14	0			99.3
625.01	LB14	0			96.8
972.01	CFOP	0			–
3728.01	LB14	0			99.6
Group C – Unsolved cases					
1463.01	CFOP	1	5.47''	6.9 (Kep.)	–
3890.01	LB14	0			98.3

Notes. Uncertainties in the angular separation of the companions and in their magnitude difference have been omitted for clarification purposes. We refer to the corresponding references for more information about this. ^(a) LB12 = Lillo-Box et al. (2012), L13 = Law et al. (2014), LB14 = Lillo-Box et al. (2014c), CFOP = no reference found in the bibliography but companion tables of the UKIRT *J*-band survey by D. Ciardi are available in the CFOP. ^(b) The maximum angular separation explored in Law et al. (2014) is 2.5 arcsec.

than 170 KOIs were observed and analyzed, including 9 out of the 13 KOIs studied here. For the remaining targets, we used ancillary high-resolution images from Law et al. (2014) and the UKIRT *J*-band survey⁵ of the *Kepler* sample, which are publicly available in the CFOP and provided by D. Ciardi.

In Table 1 we summarize the main results obtained for each of the KOIs of the present study, including the calculated blended source confidence (BSC) and the number of detected visual companions closer than 6.0 arcsec. The BSC parameter was presented in Lillo-Box et al. (2014a) and represents a standard and unbiased procedure for deriving the probability of a given source to be isolated (i.e., without any blended undetected sources). Additional sources were found closer than 6.0 arcsec in just two KOIs (KOI-0131 and KOI-1463). However, these visual companions are too faint to affect the CAFE spectrum, and thus their contribution to the RV is negligible. Added to this, they lie completely outside of the CAFE fiber (with 2.1 arcsec of diameter), thus not contaminating the spectra of the KOIs.

2.3. CAFE observations and data reduction

We have obtained multi-epoch RV data for the 13 KOIs shown in Table 1. We used the CAFE instrument (Aceituno et al. 2013) mounted on the 2.2m telescope at Calar Alto Observatory (Almería, Spain) to obtain high-resolution spectra ($R = 59\,000\text{--}67\,000$) in the optical range (4000–9000 Å). Table 2 summarizes the targets observed, the number of epochs acquired, and the timespan (defined as the time between the first and last spectra obtained) for each of them.

⁴ https://archive.stsci.edu/kepler/data_search/search.php

⁵ <http://keplergo.arc.nasa.gov/ToolsUKIRT.shtml>

Table 2. Kepler objects of interest analyzed in this work.

KOI	m_{Kep} (mag)	RA (HH:MM:SS.SS)	Dec (DD:MM:SS.SS)	Period ^a (days)	$M_{\star}^b$ ($M_{\odot}$)	R_{comp}^c ($R_{\odot}$)	Nspec	T_{span} (days)
Group A – Eclipsing binaries								
340.01	13.1	19:50:39.52	47:48:05.01	23.673188 ± 0.000014	1.10 ± 0.07	$0.231 \pm 0.021^{\dagger}$	21	321.1
371.01	12.2	19:58:42.28	40:51:23.37	498.3928 ± 0.0042	1.55 ± 0.15	0.77 ± 0.39	29	722.0
686.01	13.6	19:47:21.78	43:38:49.64	52.513565 ± 0.000015	0.84 ± 0.12	$0.1248 \pm 0.0038^{\ddagger}$	19	39.0
3725.01	10.1	19:40:48.69	38:31:10.38	$1.5704970 \pm 0.0000004^d$	2.52 ± 0.53	0.825 ± 0.007	10	17.0
3853.01	10.6	19:11:13.73	43:11:19.62	21.512905 ± 0.000050	1.55 ± 0.38	0.31 ± 0.22	25	70.9
Group B – Fast rotators								
12.01	11.4	19:49:48.90	41:00:39.56	17.855149 ± 0.000010	1.31 ± 0.27	0.122 ± 0.060	47	114.0
131.01	13.8	19:56:23.41	43:29:51.32	5.014233 ± 0.000002	1.31 ± 0.26	0.082 ± 0.029	29	418.0
366.01	11.7	19:26:39.40	38:37:09.32	75.11202 ± 0.00010	1.69 ± 0.17	0.097 ± 0.042	44	72.9
625.01	13.6	19:06:15.31	39:32:04.09	38.13819 ± 0.00021	1.46 ± 0.24	0.43 ± 0.21	52	66.0
972.01	9.3	18:48:00.07	48:32:32.00	13.118908 ± 0.000095	2.02 ± 0.07	0.055 ± 0.013	51	335.3
3728.01	12.3	19:35:05.31	44:38:18.49	5.5460830 ± 0.0000013	2.05 ± 0.17	0.1880 ± 0.0009	40	243.0
Group C – Unsolved cases								
1463.01	12.3	19:13:02.07	43:22:35.27	$1064.2681410 \pm 0.0001434$	1.17 ± 0.28	0.149	14	691.2
3890.01	13.2	19:09:52.29	37:57:59.90	152.82630 ± 0.00099	1.76 ± 0.34	0.3213 ± 0.0091	22	305.2

Notes. Observational data obtained with CAFE at Calar Alto Observatory. ^(a) Transit periods are obtained from [Borucki et al. \(2011\)](#) and [Batalha et al. \(2013\)](#). ^(b) Stellar masses are obtained from [Huber et al. \(2014\)](#). ^(c) Radius of the transiting companions according to [Batalha et al. \(2013\)](#). ^(†) This radius was obtained from our own transit fitting (see Sect. 4). ^(‡) In this case, the radius of the companion was obtained from [Díaz et al. \(2014\)](#). ^(d) In Sect. 4, we have demonstrated that the actual period of this system is twice this value, i.e., 3.1409940 ± 0.0000008 days.

We used the standard reduction process for the CAFE spectra, already described in [Lillo-Box et al. \(2014b,c\)](#). The basic reduction is performed by using the observatory pipeline described in [Aceituno et al. \(2013\)](#)⁶. The wavelength-calibrated spectra are then analyzed with our own routines in order to obtain the RV. In the case of the rapid rotators, we used the genetic algorithm *GAbox* (presented in [Lillo-Box et al. 2014c\)⁷ to determine the RV at the different epochs. We used the theoretical equivalency between maximum likelihood and cross-correlation presented in \[Zucker \\(2003\\)\]\(#\) to match the observed spectrum to a synthetic template of the same spectral type. This RV extraction process is fully described in \[Lillo-Box et al. \\(2014b\\)\]\(#\).](#)

For the slow rotators, a more precise analysis can be done by using the cross-correlation technique ([Baranne et al. 1996](#)). We used a binary weighted mask as template ([Pepe et al. 2002](#)) and cross-correlated the observed spectra against it. The mask was designed by using a solar spectrum obtained from the solar atlas provided by BASS 2000⁸. From this spectrum, we selected a series of isolated, sharp, and high-contrast absorption lines. In total, our mask includes around 2100 lines in the CAFE spectral range. We used a velocity range of $\pm 30 \text{ km s}^{-1}$ around the expected RV value for each case. The RV of each spectrum is measured as the peak of a Gaussian fit to the resulting cross-correlation function (CCF). This velocity is then corrected from the barycentric Earth radial velocity (BERV) obtained from the corresponding Julian date at mid-exposure.

In Tables A.1 to A.13, we provide the calculated radial velocities and the observing information (signal-to-noise, Julian date, and phase) for each epoch and KOI.

3. Radial velocity analysis

The extracted RV data explained in the previous section was analyzed by using the RVLIN software⁹ ([Wright & Howard 2009](#)) and its additional package BOOTTRAN for parameter uncertainties estimation with bootstrapping ([Wang et al. 2012](#)) to fit our RV data to a Keplerian orbital solution. The calculated uncertainties of the parameters account for both the RV and the stellar mass uncertainties. In this section we study five eclipsing binaries (Group A), six fast-rotating KOIs (Group B), and provide some hints of the presence of stellar-mass companions to two still unsolved KOIs in our sample (Group C). We note that the nature of the transit on KOIs of both Group B and C remains unsolved with the current data. In the former, owing to the impossibility of getting accurate RV measurements and the latter because of the lack of good phase coverage. Tables 3 and 4 summarize our RV analysis for the three groups of KOIs. We also review the high-resolution images of these KOIs already published in [Lillo-Box et al. \(2014a\)](#).

3.1. False positives: undiluted eclipsing binaries (Group A)

Among the candidates being presented here, we have found five candidates that show large RV variations, which are incompatible with the presence of planetary-mass companions. These variations are modulated with the same period as detected by the transit method using *Kepler* data. In the following, we analyze each of these false positives. In Table 3 we present the fitted orbital and physical parameters for those KOIs with a clear Keplerian fit to the RV. Figure 1 shows the measured radial velocities and the corresponding RV models of these KOIs¹⁰.

⁶ This pipeline was developed by Sebastián Sánchez.

⁷ This algorithm has been already used to confirm the planetary nature of Kepler-91b in [Lillo-Box et al. \(2014b,c\)](#) and as a spectral energy distribution fitter in [Riviere-Marichalar et al. \(2013, 2014\)](#).

⁸ http://bass2000.obspm.fr/solar_spect.php

⁹ <http://exoplanets.org/code/>

¹⁰ KOI-3725 is not presented in this figure because its large $v \sin i$ prevents an accurate RV study.

Table 3. Results of the fitting to the observed radial velocities.

KOI	K (km s ⁻¹)	e	ω (deg)	V_{sys} (km s ⁻¹)	$M_{\text{comp}} \sin i^a$ ($M_{\odot}$)	inc. ^b (deg)	F_M^c (M_{Jup})	a (AU)	F-test ^d
Group A – Eclipsing binaries									
0340 B	16.28 ± 0.11	0.5138 ± 0.0059	239.71 ± 0.58	-84.007 ± 0.045	0.2144 ± 0.0058	89.95	7.000 ± 0.091	0.1614 ± 0.0054	>100
0371 B	8.252 ± 0.086	0.4070 ± 0.0081	94.75 ± 0.47	-56.855 ± 0.081	0.445 ± 0.014	89.95	23.15 ± 0.82	1.424 ± 0.047	>100
0686 B	6.3 ± 1.7	0.52 ± 0.15	63 ± 12	-31.30 ± 0.65	0.089 ± 0.018	89.38	0.88 ± 0.45	0.259 ± 0.015	>100
3853 B	26.98 ± 0.48	0.3956 ± 0.0084	130.8 ± 1.3	-75.19 ± 0.15	0.527 ± 0.043	50.42	35.5 ± 2.2	0.175 ± 0.014	>100
3853 C	2.1 ± 1.3	0.56 ± 0.20	312 ± 21	-75.19 ± 0.15	0.030 ± 0.016	–	0.011 ± 0.019	0.171 ± 0.014	>100
Group C – Unsolved cases									
1463 B	>3.3	>0.18	[80,200]	[-28.5,-25.5]	>0.183 ± 0.030	89.95	>4.15	2.15 ± 0.19	>100
3890 B	>2.5	>0.33	[0,82]	[-28.7,-24.2]	>0.097 ± 0.014	89.95	>0.27	0.676 ± 0.040	3.6

Notes. ^(a) Companion mass assuming primary mass from [Huber et al. \(2014\)](#), see Table 2. ^(b) Orbital inclination provided by the Kepler team. ^(c) Mass function, defined as: $F_M = M_{\text{comp}}^3 \sin^3 i / (M_{\text{comp}} + M_{\star})^2$. This parameter is directly obtained from the RV fit and does not depend on the primary mass. ^(d) F-test comparing the significance of the RV model to a straight line.

Fig. 1. Radial velocity analysis of the detected binary systems. In each set of images and for every KOI, we show the periodogram of the radial velocity data (*upper panel*), the fit to the data according to Sect. 3.1 (*middle panel*), and the residuals of the fit (*lower panel*).

KOI-0340.01

This planetary candidate was announced by the *Kepler* team in the first release of the mission (Borucki et al. 2010), and it still remains as a planetary candidate in the CFOP. Its *Kepler* light curve presents transit-like dims every 23.673188 ± 0.000014 days. Our analysis of the *Kepler* light curve of this KOI in Sect. 4 provides the detection of a secondary eclipse. We can therefore keep the calculated period for the companion¹¹.

This object has already been included in the catalog of eclipsing binaries¹² presented and updated in Matijević et al. (2012). Also, Santerne et al. (2012) used the SOPHIE instrument to obtain two RV measurements at quadrature phases assuming circular orbit, and derived a semi-amplitude of $K = 34.577 \pm 0.074$ km s⁻¹ with this assumption, finally concluding that this system should be a single-line spectroscopic binary. Our CAFE data (obtained at eight different phases) provides a highly eccentric orbit ($e = 0.513 \pm 0.005$) for the companion (in good agreement with the location of the secondary eclipse, see Sect. 4). The fitted RV semi-amplitude provides a value of $K = 16.28 \pm 0.11$ km s⁻¹. Assuming a host mass of $M_\star = 1.10 \pm 0.07 M_\odot$ provided by the CFOP, we derived a stellar mass for the transiting object of $M_2 \sin i = 0.214 \pm 0.006 M_\odot$. The L-S periodogram indicates a period for the RV data in good agreement with the period obtained with the transits method, thus indicating that both effects are produced by the same object (see Fig. 1). The non-planetary nature of the object transiting KOI-0340 is thus clear from this analysis so that we can firmly and definitively discard this candidate as a planet.

KOI-0371.01

A periodic transit signal of $P_{\text{orb}} = 498.3928 \pm 0.0042$ days was detected by *Kepler* for this star. No significant difference in the depth of the two single eclipses is found in this case, so we maintain the period of this KOI as calculated by the *Kepler* team. The analysis of our RV data (with a timespan of 722 days) shows large relative variations for the stellar host. We find a clear (although broad) peak in the RV periodogram corresponding to the same periodicity as the transit signal (see Fig. 1). According to our fit of the RV modulations, we find that the companion source should have a minimum mass of $M_2 \sin i = 0.445 \pm 0.014 M_\odot$. The physically bound stellar companion is calculated to be at $a = 1.424 \pm 0.047$ AU, with a highly eccentric orbit of $e = 0.407 \pm 0.008$. Thus, we can reject this planetary candidate and establish its binary nature.

KOI-0686.01

This planet candidate was released in the second catalog of *Kepler* planet candidates. The RV analysis reveals large variations with a clear modulation. The analysis of the AstraLux images of this object (see Sect. 2.2) yielded a 0.1% of probability that this KOI has an undetected blended background star. Thus, it is highly probable that these RV variations come from a bond companion to the KOI-0686 system.

The analysis of the detected transits by the *Kepler* team provided an orbital period of $P_{\text{orb}} = 52.513565 \pm 0.000015$ days. If we assume the same period and mid-transit time for the RV signal, we can obtain a model solution for the RV data. This fit

provides a stellar mass for the companion transiting object of $M_B \sin i = 0.089 \pm 0.018 M_\odot$, thus confirming its stellar nature. We can thus confirm that KOI-0686 is an eclipsing binary. We note that a contemporary work by Díaz et al. (2014) also obtained the same conclusion, with the fitted parameters in good agreement within the uncertainties.

KOI-3725.01

The observations for this object were started while its status was “not-dispositioned” in the *Kepler* catalog. This meant that the light curve analysis had not yet passed all the required criteria to be considered as a planet candidate. After the target was observed with CAFE, the *Kepler* team updated its status to “false positive”. Our analysis of the light curve in Sect. 4 shows a clear difference in the depth of the odd and even eclipses, thus tagging this system as an eclipsing binary. Given this, we must consider a double period such as the one published by the *Kepler* team (i.e., $P_{\text{orb}} = 3.1409940 \pm 0.0000008$ days instead of 1.5704970 ± 0.0000004 days).

Our high-spectral resolution data (and light curve analysis in Sect. 4) confirm that this system is an eclipsing binary, showing large RV variations over the observed timespan. However, the small number of phases acquired and the contaminated spectrum by the presence of two possible sets of lines, with a very broad one (suggesting high rotational velocities) prevent us from performing any detailed RV analysis.

KOI-3853.01

This KOI has been reported as a possible false positive in the *Kepler* database¹³. The derived period according to the light curve analysis is $P_{\text{orb}} = 21.512905 \pm 0.000050$ days. The analysis of our high-resolution spectra obtained in 14 different phases reveals a large RV variation. When fitting the RV with a single object, an important periodic trend is found in the residuals. We tried to fit the RV data by assuming the presence of a third body in the system (see Fig. 2). The fit in this case was significantly improved. We can measure the significance of such improvement by using the Bayesian inference criterion¹⁴ (BIC). We obtain a difference in the BIC value of $\Delta\text{BIC} > 100$, showing very strong evidence of a third companion.

Interestingly, the period of the less massive companion (i.e., component C) is similar (in agreement within 3σ uncertainties) to the more massive companion (i.e., component B), hence in a near 1:1 mean motion resonance (MMR). The periodogram of the RV data shows a double (blended) peak around the period corresponding to the the eclipse observed in the *Kepler* data. Both peaks have a false alarm probability (FAP) below 1%. To test the validity of the second periodicity in the data, we fixed the fitted parameters obtained for component B and ran 10×10^5 MCMC chains to fit the residuals of the data. We let the period of the possible C component vary in the range 1–71 days. The posterior distribution of the combined chains clusters around the estimated period provided by the joint fit (within the uncertainties).

Thus all these three tests performed with our RV data (BIC, periodogram, and MCMC analysis) favor the existence of a third component in 1:1 MMR against the two-bodies-only configuration. The orbits of the two possible companions would be

¹¹ If differences in the odd/even transit depths are found, we should double the period since we would be seeing the two eclipses of an eclipsing binary.

¹² http://archive.stsci.edu/kepler/eclipsing_binaries.html

¹³ <http://exoplanetarchive.ipac.caltech.edu>

¹⁴ $\Delta\text{BIC} = (\chi_1^2 - \chi_2^2) - (k_1 - k_2) \ln N$, where χ_1^2 and k_1 are the χ^2 statistic and the number of free parameters for the one-companion model and χ_2^2 and k_2 are the χ^2 statistic and the number of free parameters for the two-companions model. N is the number of RV points.

Fig. 2. Radial velocity analysis of the detected components of KOI-3853. *Upper panel* shows the RV solution for the whole system (black solid line) and the two contributions of the B component (dashed blue) and C component (dashed purple). *Lower panels* show the individual contributions of components B (*left panel*) and C (*right panel*).

oriented in opposition, i.e., the difference in the argument of the periastron of both eccentric orbits agrees with being 180° . According to the fitted models, and assuming the stellar mass for the A component provided in Table 2, the minimum masses of the two companions would be $M_B \sin i_B = 0.527 \pm 0.044 M_\odot$ and $M_C \sin i_C = 0.030 \pm 0.016 M_\odot$. The mass difference between both components is significantly large, with the less mass component in the substellar regime.

The unusual architecture of the proposed scenario would require a more detailed study of its stability (which is beyond the scope of the present paper). Simulations of 1:1 mean motion resonances in the planetary-mass regime by Antoniadou et al. (2014) show that these configurations are stable under specific mass ratio conditions, $m_C/m_B < 0.0205$. Although our objects are more massive, we note that this condition is fulfilled (within the uncertainties) for the KOI-3853 system. However, as stated before, more work is needed to analyze the stability of this system.

Stellar pulsations induced by the companion could also explain the correlated residuals in the RV fit. As we see in Sect. 4, the light curve of this target presents the so-called *heartbeat* effect, which is produced by tidal interactions induced by the more massive stellar companion. In Willems & Aerts (2002), the authors describe and calculate the RV variations induced by tides in close binary systems. According to them, there are specific resonant configurations that can lead to radial velocity variations that are even greater than 5 km s^{-1} , thus a relevant explanation for the presence of the modulated residual of this close binary. However, an accurate description of this system is beyond the scope of this work. Future analysis that studies the heartbeat-like modulation

and the stellar modes induced by the close massive companion could unveil or reject the existence of the substellar companion in the 1:1 resonance orbit.

3.2. Fast rotators (Group B). Upper limits to companion masses

Planets orbiting fast-rotating stars are more difficult to detect by the RV method. The line broadening produced by this effect prevents an accurate measurement of the line shift, significantly increasing the uncertainties for high $v \sin(i)$ values. Six fast rotators ($v \sin(i) > 20 \text{ km s}^{-1}$) were found in our sample. We computed individual spectral templates with the same physical properties (effective temperature, surface gravity, metallicity, and rotational velocity) as the KOI by using the ATLAS09¹⁵. Then *GAbbox* was used to compare the template and the observed spectra and to determine the shift between both (i.e., the RV), by following the theoretical equivalency between maximum likelihood and cross-correlation presented in Zucker (2003)¹⁶.

As stated, we can just provide an upper limit to the mass of the companion of these KOIs. We have assumed circular orbits for all of them, as well as the lack of blended companions contaminating the RV data (see Table 1). A simple circular model was fitted to the RV data by fixing the period and time of mid-transit calculated by the Kepler team from the analysis of the eclipse. Thus, only two free parameters were fitted, the

¹⁵ <http://kurucz.harvard.edu/grids.html>

¹⁶ See Lillo-Box et al. (2014b) for a complete description of the method with *GAbbox*.

RV semi-amplitude (K) and the systemic velocity (V_{sys}). We ran one MCMC chain of 10^6 steps and discarded the first 10% to avoid dependency on the priors. The results for all six fast rotators are presented in Table 4. According to these results, all KOIs but KOI-3728 are compatible with having $K = 0 \text{ km s}^{-1}$ (non-detection) within the uncertainties. Thus, we can take $\sigma_{\text{RV}} = K + 3 \times \sigma_K$ (where σ_K is the uncertainty in K) as the upper limit of the semi-amplitude of the RV variations caused by an undetected companion. In the case of KOI-3728, the solution for K is not compatible with zero, thus suggesting a possible detection of the RV variations provoked by the transiting companion. According to this analysis, the companion would have a mass of $0.068 \pm 0.041 M_{\odot}$. However, owing to the large uncertainties and for consistency with the structure of this paper, we prefer to maintain this KOI in this group B, although highlighting the possible detection of a stellar-like companion. The large $v \sin i$, instead, does not allow us to ensure such a detection.

As a result, the RV amplitude (K) induced by the companion (if any) detected in these KOIs should be smaller than the aforementioned upper limit (σ_{RV}), i.e. $K < \sigma_{\text{RV}}$. This amplitude is defined for circular orbits as

$$K^3 = \frac{2\pi G}{P} \left(\frac{M_{\text{comp}}^3 \sin^3(i)}{(M_{\text{comp}} + M_{\star})^2} \right), \quad (1)$$

where the term in parenthesis is called the mass function (F_M), $M_{\star}$ is the stellar mass, M_{comp} is the mass of the companion, and P its orbital period. We can now determine the maximum mass of the companion that accomplishes $K = \sigma_{\text{RV}}$. This value represents the maximum mass ($M_{\text{comp}}^{\text{max}} \sin i$) of the hypothetical companion orbiting the star and inducing the detected transit signal. The calculated maximum masses of the hypothetical companions ($M_{\text{comp}}^{\text{max}} \sin i$) are listed in Table 4.

All but two KOIs (KOI-0972 and KOI-3728) have upper mass limits below the substellar regime ($\sim 80 M_{\text{Jup}}$). Indeed, in one case (namely KOI-0366), the upper mass limit is below the deuterium-burning limit ($\sim 13 M_{\text{Jup}}$), suggesting that the object transiting this star is likely a planet.

3.3. Unsolved cases (probable false positives, Group C)

KOI-1463.01

Only four phases (14 spectra in total) have been obtained with CAFE for this long-period candidate ($P_{\text{orb}} = 1064.2681410 \pm 0.0001434$ days). Our RV data (with a timespan of 691 days) shows large variations of $\sim 7.5 \text{ km s}^{-1}$, which do not correspond to a planetary-mass object (see Fig. 3, left panel). However, the low number of epochs acquired and the timespan (shorter than the orbital period) prevents us from extracting definite conclusions about this system. We used a radial velocity model including non-zero eccentricity to fit the available data. The free parameters used were thus the RV semi-amplitude, the eccentricity, the argument of the periastron, and the systemic velocity of the system.

We ran a Monte-Carlo Markov-Chain with 10^6 steps to estimate these parameters and detect the correlations between them because of the lack of a complete sampling of the orbital phases. The degeneracy in the parameter space is important, but we must point out that all solutions provide eccentricities that are higher than $e > 0.18$ and semi-amplitude values higher than $K > 3.3 \text{ km s}^{-1}$. This corresponds to a lower mass limit for the companion transiting object of $M_{\text{B}}^{\text{min}} = 0.183 \pm 0.030 M_{\odot}$. In the left panel of Fig. 3, we show a random sample of solutions obtained for this system.

The transiting companion is probably a star, according to the present data, suggesting that KOI-1463.01 is a false positive. The solution to this system is still open, and more RV data in a longer timespan (since *Kepler* will no longer observe this target) will help solve this dichotomy, unveiling the nature and properties of the transiting object. We also note that Hirano et al. (2012) suggest that this candidate could actually be a late-type stellar companion transiting the star, which they base on their analysis of the flux variations.

KOI-3890.01

This planet candidate was detected as transiting its host star with a periodicity of 152.82630 ± 0.00099 days. Our RV analysis shows a clear trend with a variation of 3 km s^{-1} in a timespan of 305.2 days (see Fig. 3, right panel). Since we do not detect transit depth differences in the odd and even transits, we can fix the period and mid-transit time to what was measured in the light curve analysis by the Kepler team. Also, the narrow range of phases covered by our observations ($\phi \in [0.6, 0.8]$) means that we cannot constrain the eccentricity and argument of the periastron of the orbit. We then proceed in the same manner as with KOI-1463 by running an MCMC chain and analyzing the range of parameters. By doing so, we obtain a minimum RV semi-amplitude of $K > 2.5 \text{ km s}^{-1}$. This translates into a minimum mass for the transiting companion such that $M_{\text{B}} > 0.097 \pm 0.014 M_{\odot}$, with a minimum eccentricity of $e > 0.33$. In the right hand panel of Fig. 3, we show a random sample of solutions for this degenerated system.

However, we must warn that in this case, the F-test comparing the RV model to a simple straight line provides a value of 3.6, slightly favoring the false positive detection against a null detection model. Thus, although this candidate is likely to be a binary, we cannot draw definite conclusions given the current data (mainly owing to the small phase coverage). More RV at different phases is needed to better understand this system.

4. Light curve analysis

In this section we analyze the *Kepler* light curves of the targets studied in this work to look for possible interesting features that can contribute to better characterizing these systems (secondary eclipses, photometric natural modulations – ellipsoidal, beaming, or reflexion- and signatures of possible additional objects) in the manner as we did in Kepler-91 (Lillo-Box et al. 2014c). We note that the accuracy of some parameters (such as the eccentricity) could benefit from a joint analysis of the RV and the LC. However, in the particular cases studied in this paper, the eccentricity of the orbits are well constrained with the RV data (since most of the orbits are sampled well), and we assume the period and time of transit from the analysis of the LC by the Kepler team. Thus, we consider that the joint analysis would not improve the results significantly in the present cases.

In the next sections, we individually analyze the results of the targets where additional effects (rather than the detected transit by *Kepler*) have been found.

KOI-0340

We have detected the secondary eclipse (see Fig. 4) of this RV-identified binary orbiting in a highly eccentric orbit (see Sect. 3.1). We used a simple fitting model of a binary box with linear ingress and egress dependencies (enough for the purposes of the paper) to measure its depth, location, and duration. The period and time of mid eclipse was assumed from the

Fig. 3. Radial velocity analysis of the unsolved systems (Group C, see Sect. 3.3). We show one hundred random solutions accepted in our MCMC run (see Sect. 3.3). The residuals to the median solution are found in the *lower panel*.

Fig. 4. Detrended *Kepler* light curve of KOI-0340. In all panels small gray circles represent the *Kepler* data and the red filled circles is a binning of the whole data with a bin size of 0.005 in phase. *Upper panel* shows a zoom to the primary transit and the fitted primary eclipse with a solid black line (see Sect. 4). *Middle panel* shows the detected secondary eclipse and the fit obtained in Sect. 4 as a solid black line. *Lower panel* shows the residuals of the fit, with a standard deviation of 173 ppm in the original dataset and 36 ppm in the binned light curve.

one calculated by the *Kepler* team. The results show a depth of $\delta_2 = 650.6 \pm 6.6$ ppm, located at $\phi = 0.31862 \pm 0.00002$ and lasting $d = 0.01005 \pm 0.00023$ in phase units, equivalent to $d = 5.70 \pm 0.13$ hours when assuming the period provided by *Kepler* team. By assuming the primary eclipse depth provided by the *Kepler* team ($\delta_1 = 22335$ ppm, no uncertainty provided), we can derive a surface temperature ratio with

$$\frac{\delta_1}{\delta_2} = \left(\frac{T_A}{T_B} \right)^4, \quad (2)$$

Table 4. Upper limits for the mass of the transiting companion to KOIs with large $v \sin i$ values (fast rotators, Group B).

Group B – Fast rotators					
KOI	$v \sin i$	K (km s ⁻¹)	V_{sys} (km s ⁻¹)	σ_K (km s ⁻¹)	$M_{\text{comp}}^{\text{max}} \sin i$ (M_{Jup})
12.01	70 ± 5^a	0.140 ± 1.425	-18.6 ± 1.1	1.565	25.2 ± 3.7
131.01	$26^{†,b}$	1.400 ± 1.995	-9.0 ± 1.8	3.395	35.8 ± 5.0
366.01	35 ± 2^c	0.027 ± 0.255	8.5 ± 0.2	0.282	8.70 ± 0.59
625.01	25 ± 2^c	0.120 ± 0.510	-25.87 ± 0.42	0.630	14.1 ± 1.6
972.01	120 ± 5^c	2.200 ± 3.300	-14.1 ± 2.4	5.500	106.8 ± 2.6
3728.01	$55^{†,d}$	4.810 ± 2.775	-52.6 ± 2.4	7.585	111.6 ± 6.3

Notes. ^(†) No uncertainties provided. ^(a) Values obtained from the analysis of TrES spectra by Byerla. ^(b) Values obtained from the analysis of Lick spectra by Isaacson. ^(c) Values obtained from the analysis of McDonald or TrES spectra by Quinn.

where δ_1 is the depth of the deepest eclipse, δ_2 the depth of the smaller eclipse, and T_A/T_B the ratio of effective temperatures of both stars. By using this equation, we obtain a temperature ratio of $T_A/T_B = 2.421 \pm 0.006$.

Also, as expected by the high eccentricity and orientation of the orbit (obtained by the RV analysis), the location of the secondary eclipse is not centered at the mid time phase but instead at $\phi = 0.31862 \pm 0.00002$. The expected phase difference is known to be given by (Wallenquist 1950)

$$\Delta\phi = 0.5 + e \cos \omega \frac{1 + (1/\sin i)^2}{\pi}. \quad (3)$$

According to the parameters obtained with the RV analysis, we would have expected the secondary eclipse to be located at $\phi = 0.335 \pm 0.010$, if we assumed the inclination provided by the *Kepler* team. The difference between the expected time of mid eclipse and the measured time is 9.3 ± 5.7 h. The source of this discrepancy is unknown but could be an underestimation of the uncertainties in the RV parameters or an inaccurate determination of the time of eclipse, translated into a small shift in the phase-folded light curve.

Owing to the high eccentricity found for this system in Sect. 3.1, we decided to perform a dedicated modeling of the primary eclipse¹⁷. We used the Mandel & Agol (2002) light

¹⁷ The *Kepler* team assumes circular orbits in the transit fitting.

Fig. 5. Detrended *Kepler* light curve of KOI-3725 and phase-folded by using the new calculated period (i.e., $P_{\text{orb}} = 3.1409940 \pm 0.0000008$ days), twice the one published by the *Kepler* team. The unequal depth of odd/even transits is clear evidence of the binary nature of this object. *Upper panel* shows the entire phase of the system. *Lower panel* shows a zoom to the odd and even transits (in different colors and symbols). The primary transit has been shifted to $\phi = 0.5$ for comparison purposes. The transit model is shown as solid gray lines.

Fig. 6. Detrended *Kepler* light curve of KOI-3853 and phase-folded using the period published by the *Kepler* team. The upper panel shows the entire phase to show the heartbeat effect. The red line shows the spline function fit to remove the effect. Vertical dotted lines show the region zoomed in Fig. 8.

curve models and obtained the quadratic limb-darkening parameters by interpolating the stellar parameters provided by Huber et al. (2014) to the values in Claret & Bloemen (2011) for the *Kepler* band. We fixed the eccentricity and argument of the periastron to the values found in the radial velocity analysis and leave the inclination (i), semi-major axis to primary radius (a/R_A), and radius ratio (R_A/R_B) as free parameters. The results for this fit are $i = 89.6^\circ \pm 0.2^\circ$, $a/R_A = 21.82 \pm 0.34$, and $R_B/R_A = 0.1452 \pm 0.0007$. This model is shown in the upper panel of Fig. 4. The main difference with the *Kepler* team

Fig. 7. Variation in the eclipse depth of the KOI-3853 system in the timespan of *Kepler* observations.

parameters ($i_{\text{Kep}} = 89.95^\circ$, $(a/R_A)_{\text{Kep}} = 14.31983 \pm 0.00722$, and $(R_B/R_A)_{\text{Kep}} = 0.142771^{+0.000068}_{-0.000048}$) is the semi-major-to-stellar-radius ratio. This is due to their assumption of circular orbit, while we have found a relatively high value for the eccentricity from both the RV and the secondary eclipse analyses.

KOI-3725

The most remarkable imprint in the light curve of KOI-3725 when phase-folding it with the period provided by the CFOP is the clear presence of two sets of eclipses with different depths. If we phase-fold the LC with twice the current period, we obtain a deeper eclipse at phase $\phi = 0$ than at $\phi = 0.5$. This is a clear sign of an eclipsing binary. According to this, the actual periodicity of this binary system is $P_{\text{orb}} = 3.1409940 \pm 0.0000008$.

The temperature ratio between both stars can be estimated from the depth ratio of both eclipses following Eq. (2). In this case, a simple fitting to the Gaussian-like eclipses (enough for the purposes of this paper) provides $\delta_1 = 2732 \pm 30$ ppm and $\delta_2 = 1803 \pm 35$ ppm (see fitted functions overplotted in the bottom panel of Fig. 5). This implies a temperature ratio of $T_A/T_B = 1.109 \pm 0.006$.

KOI-3853

The light curve of KOI-3853 shows an interesting effect just discovered in a few tidally distorted binaries, the *heartbeat* pulsation. The shape of the light curve modulation due to this effect is well understood and was parametrized by Kumar et al. (1995). In particular, in the case of KOI-3853, its shape corresponds to a highly inclined orbit with the periastron oriented behind the plane of the sky. An accurate model fitting of this modulation is beyond the scope of this paper, but future works will focus on this object and characterize it fully.

However, the *heartbeat* is not the only imprint in the light curve of this system. A transit-like shape appears in the middle of the tidal modulation in the phase-folded light curve. The *Kepler* team identified this transit as a potential candidate that has a planetary nature. In the lower panel of Fig. 6, we show a zoom to this region once the “heartbeat” effect has been removed by a simple cubic spline fitting. The eclipse has a maximum depth of around 2000 ppm. However, it is filled by some data points at lower depths. The period of both the heartbeat signal and the eclipse are exactly the same, indicating that both effects are provoked by the same object (i.e., companion B). Interestingly, we can see both a duration and depth variation in the individual eclipses (see Fig. 7). Figure 8 displays the individual (detrended) eclipses.

Fig. 8. Individual eclipses in the KOI-3853 system discussed in Sect. 4. The color code represents the transit number (equivalent to the Julian date) since $\text{BJD} = 2454966.6$ days. The filled circles show the location (timing and depth) of the peak of the eclipse for each individual transit. We have omitted timespans in which *Kepler* data is not available at the phases of interest. The light curve has been firstly detrended and then removed from the heartbeat effect as explained in Sect. 4.

Our RV analysis (see Sect. 3.1) suggests that the motion variations of the primary star (A) are described well with the presence of two companions, a massive stellar object (component B) and a substellar companion (component C) in a near 1:1 mean motion resonance. Both objects would revolve in eccentric orbits around the primary (massive) star. Based on this, we suggest some possible explanations here for the depth and duration variation of the detected eclipses:

- *Orbital wobble due to satellite companion.* The presence of a third-body orbiting component B can periodically vary the impact parameter of the latter, thus changing both the duration and the depth of the eclipse. Since we know from the shape of the heartbeat effect that the orbital inclination should be high, this should be a grazing eclipse of component B over component A. In the first periods of Fig. 8, the projected location of component B in the plane of the sky would be at impact parameters $b \gtrsim 1 + R_B/R_A$ so that we see a small eclipse or no at all. By contrast, in the last periods observed, the impact parameter decreases so that the eclipse is deeper. A longer timespan could have confirmed this hypothesis by detecting periodic variations of the eclipse depth.
- *Orbital wobble due to component C.* In our RV analysis we found that the observed RV signal is modeled much better with two co-orbital stars with the same periodicity (in 1:1 mean motion resonance) but in two eccentric orbits in opposition, i.e., with their pericenters differing by 180° . Component C, maybe in a higher inclined orbit (since we do not see any other dip in the LC), could be perturbing the orbit of component B, provoking an orbital wobble able to change its impact parameter and thus the eclipse depth.
- *Orbital circularization.* If the system is being circularized, with component B orbiting closer to component A every

period, the eclipse depth and duration will be increased with time. Since within the timespan of *Kepler* data, we do not see a new turn back to smaller depths, we cannot discard this possibility.

With the current data, none of the previous conclusions can be discarded so that the problem remains open. However, our RV analysis suggests the presence of a third component in near 1:1 mean motion resonance. Future observations and study will shed more light on this and will try to unveil the nature of this system. In particular, a dedicated stability study is required to check the dynamical plausibility of the co-orbiting substellar object in 1:1 mean motion resonance. As we mentioned in Sect. 3.1, the mass ratio between the two companions would agree with the allowed ratio for a triple system in 1:1 mean motion resonance as calculated by Antoniadou et al. (2014), although we warn that this study was specifically performed for planetary-mass systems.

5. Summary and discussion

We have analyzed the RV data obtained with the CAFE spectrograph for 13 KOIs and the *Kepler* light curves of some of them. In the majority of the eclipsing binaries found in this work (Group A), we found that the lighter component is a very low-mass stars (VLMSs). Zhou et al. (2014) and Díaz et al. (2014) have published the latest results on this kind of object (see also references there in), adding more examples to the reduced number of well-characterized VLMSs (with detected eclipses and RV variations). Added to this, our RV analysis suggests substellar masses for the transiting companions of the fast-rotating stars (Group B).

In Fig. 9, we show the mass-radius diagram for the companions found around these KOIs. In the case of KOI-0340 B, the

Fig. 9. Mass-radius diagram of the companion objects with $M < 0.3 M_{\odot}$ found to some of the analyzed KOIs in groups A and B. The open square shows the location of the possible third body in the KOI-3853 (i.e., KOI-3853 C), with an ad hoc assumed radius of $0.1 R_{\odot}$. The dotted vertical error bar indicates our unknown about its actual size, see Sect. 5. We used the isochrones of 1 Gyr and 5 Gyr (from top to bottom) from Baraffe et al. (1998) for solar metallicity (dotted dark blue line) and $[\text{Fe}/\text{H}] = -0.5$ (dashed light blue line). In the case of masses below $0.1 M_{\odot}$, we used the Baraffe et al. (2003) isochrones (dotted-dashed gray lines) of 1, 5, and 10 Gyr (from top to bottom). The arrows in the Group B KOIs indicate that their masses are just upper limits. The dashed regions illustrate the range of masses allowed for the KOI-0972 planet candidates (see Sect. 5). For reference, we have plotted the known planets with provided masses and radius published in the exoplanet encyclopedia (www.exoplanet.eu) as light blue plus signs.

radius provided by the Kepler team was well below the expected value provided by any isochrone. We then decided to make a dedicated primary eclipse fit (see Sect. 4) to account for the high eccentricity measured in Sect. 3.1. By assuming the primary radius obtained by Huber et al. (2014), the new radius of the companion, although larger, still lies below the expected value. This could be attributed to an underestimation of the radius of the primary star (R_A). We can estimate R_A from the a/R_A ratio obtained by the primary eclipse fitting and the a value obtained in the RV analysis. The resulting updated radius is $R_A = 1.589 \pm 0.021 R_{\odot}$. If we now use this value and the radii ratio between both components obtained from the eclipse fitting (R_B/R_A), we obtain $R_B = 0.231 \pm 0.021 R_{\odot}$. This new value agrees perfectly with the expected value for the calculated mass of the companion.

In the case of the fast rotator KOI-0972, the calculated upper mass limit for its transiting objects (assigning this mass limit to every candidate) also lies below the isochrones of VLMSs. The Kepler team detected two planet candidates in this system, with measured radii $R_{01} = 6.1 \pm 1.4 R_{\oplus}$ and $R_{02} = 1.73 \pm 0.57 R_{\oplus}$. There are thus two explanations for the discrepancy in the location of these objects in the mass-radius diagram: i) an underestimation of the stellar radius; or ii) a real planetary nature for the candidates, with corresponding masses well below our upper limits. The former explanation is plausible since the host seems to be a subgiant star, and the Dartmouth models used to determine the radius could be biased for this kind of stars (see Huber et al. 2014). The latter possibility is represented in Fig. 9 by the shadowed regions. We can see that they would agree with having planetary-like densities, in agreement with their measured radii, if their masses are well below our detection limits.

According to the mass-radius diagram and isochrones, we can also obtain an estimation of the radius of the suggested third component in KOI-3853 (i.e., KOI-3853 C). By assuming the calculated mass obtained by RV and the isochrones between 1–5 Gyr, the radius of this object should be in the range $R_C \approx 0.08\text{--}0.11 R_{\odot}$.

In the following sections we summarize the results of each group of KOIs.

5.1. Eclipsing binaries (false positives, Group A)

We have spectroscopically identified five eclipsing binaries in the sample of *Kepler* planet candidates via RV analysis. Among them, KOI-0340 has already been identified as a binary and KOI-3725 was initially classified as “not-dispositioned” but then updated to “false positive” after we had already obtained the spectra. We detected the secondary eclipse of KOI-0340 using *Kepler* data. By measuring its depth, we concluded that the temperature ratio of both stars is $T_{\text{eff}}^A/T_{\text{eff}}^B = 2.45 \pm 0.03$. Also, the location of the secondary eclipse agrees (except for a small offset) with the high eccentricity of the orbit derived by the RV analysis. In the case of KOI-3725, we concluded that the period of the system is actually twice the one published by the Kepler team, since we detect clear differences in the odd/even eclipse depths. The location of the secondary (less deep) eclipse confirms a circular orbit for this system.

Apart from the already confirmed false positive KOI-0686, we reported two other eclipsing binary systems in this work (namely KOI-0371.01 and KOI3853.01). They present RV variations with the same periodicity as the transit signal. The case of KOI-3853 is of particular interest. Its light curve shows the clear signs of a recently discovered class of tidally distorted binaries, also known as *heartbeat* stars. We have found that the eclipse detected by *Kepler* changes progressively in depth and duration. The high inclination of the orbit of the system (known because of the shape of the heartbeat effect) agrees with this dim being a grazing eclipse of the two stars. Our RV data suggests the presence of a third (substellar) component in the system revolving in an eccentric orbit around the primary star in a near 1:1 mean motion resonance with the more massive detected companion. Taking this into account, we hypothesize three possible explanations for the depth and duration variations: i) a third body perturbing the impact parameter on every transit; ii) an orbital wobble of component B due to the perturbing substellar companion; and iii) a possible circularization of the orbit with the stars getting closer, hence decreasing the impact parameter. This dichotomy could be solved with a longer photometric timespan. In the first and second scenarios we should see a modulation of the eclipse depth, while in the second we should just see a rise in the depth value followed by a stabilization when the circularization is reached. However, with the current data, it is not possible to discard any of these configurations. The second scenario would agree with the observed RV, but it would require a detailed stability analysis. Other configurations could also be possible but more data are needed.

5.2. Fast rotators: upper mass limits to Kepler planetary candidates (Group B)

We have presented upper mass limits for six candidates with high rotational velocities. Because of this, our CAFE observations were unable to detect any RV variations below particular limits. These limits were used to set upper limits on the masses

of the possible companions. We found that the companions (if any) to four of these KOIs (namely KOI-0012, KOI-0131, KOI-0366, KOI-0625) have substellar masses (i.e., $M < 0.08 M_{\odot}$), one of them (KOI-0366) having a maximum mass below the deuterium-burning limit and thus likely to be a true planet. In contrast, we found that KOI-3728 is very likely a false positive, since our analysis in Sect. 3.2 suggests the detection of a RV variation compatible with a stellar mass. However, the high rotational velocities prevent us from establishing any definite nature in both systems.

5.3. Unsolved cases (probable false positives, Group C)

We have analyzed two cases whose nature remains unsolved after our RV analysis. Although both of them show large RV variations that strongly suggest that they are binaries, we could not definitively unveil their nature because of the lack of enough phase coverage and the low number of data acquired. In both cases we provided limits for the different parameters in the RV fit.

In KOI-3890, we obtained a minimum mass for the transiting companion of $M_B > 0.097 M_{\odot}$, with the eccentricity of the orbit being $e > 0.33$. In the case of KOI-1463, we obtain $M_B > 0.183 M_{\odot}$ and $e > 0.18$. Thus, in both cases, the current data strongly suggests that the transiting companions are probably stellar.

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Appendix A: Radial velocity tables**Table A.1.** KOI-0012: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian Date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
66.442058	14.4	-18.3 ^{+6.5} _{-4.7}	72.463525	15.5	-18.1 ^{+3.1} _{-2.7}	87.634276	15.5	-18.5 ^{+4.6} _{-1.2}
66.454881	24.0	-9.4 ^{+5.1} _{-4.7}	76.518732	18.1	-19.2 ^{+2.4} _{-3.4}	90.630156	21.5	-18.9 ^{+3.3} _{-4.4}
66.467705	19.0	-9.6 ^{+5.6} _{-5.7}	76.533549	34.2	-17.5 ^{+1.6} _{-3.4}	115.379299	21.0	-16.5 ^{+2.8} _{-4.5}
69.439270	15.0	-18.4 ^{+7.1} _{-6.2}	76.548365	28.8	-17.6 ^{+1.6} _{-1.8}	115.391505	29.9	-18.0 ^{+2.0} _{-1.5}
69.451609	21.1	-23.0 ^{+7.2} _{-1.4}	77.602751	22.5	-21.4 ^{+3.6} _{-1.4}	115.403712	21.1	-20.7 ^{+3.3} _{-1.2}
69.463949	14.7	-19.5 ^{+6.7} _{-2.5}	77.615244	30.5	-19.0 ^{+2.1} _{-2.8}	117.381785	22.3	-18.7 ^{+2.3} _{-1.5}
70.434806	24.8	-18.1 ^{+1.7} _{-2.2}	77.627738	20.5	-13.5 ^{+3.8} _{-3.5}	117.393940	27.0	-14.3 ^{+3.6} _{-1.3}
70.447044	31.4	-20.6 ^{+1.8} _{-1.3}	78.457637	23.3	-19.3 ^{+3.5} _{-2.5}	117.406095	15.0	-20.9 ^{+8.6} _{-1.7}
70.459281	19.1	-21.8 ^{+2.8} _{-1.3}	78.472721	29.5	-19.0 ^{+1.9} _{-2.3}	129.381270	17.0	-21.9 ^{+4.8} _{-1.7}
71.431319	23.0	-18.9 ^{+2.7} _{-1.3}	78.487805	17.8	-14.8 ^{+3.9} _{-2.7}	129.393473	27.8	-20.0 ^{+2.8} _{-2.5}
71.456236	25.8	-19.2 ^{+1.5} _{-1.6}	80.406010	19.8	-21.3 ^{+4.0} _{-2.0}	129.405676	21.9	-18.7 ^{+2.0} _{-1.5}
71.532211	53.8	-16.6 ^{+1.4} _{-2.8}	80.418276	31.2	-19.8 ^{+3.0} _{-7.5}	180.442531	21.3	-21.2 ^{+3.9} _{-1.7}
71.608528	30.3	-16.6 ^{+1.6} _{-2.1}	80.430543	24.1	-17.7 ^{+2.5} _{-4.6}	180.464569	23.0	-19.5 ^{+1.9} _{-2.7}
71.632761	29.8	-19.4 ^{+1.7} _{-1.4}	82.602553	20.3	-19.6 ^{+1.7} _{-1.7}	180.464653	41.1	-19.6 ^{+1.8} _{-2.1}
72.439229	23.2	-17.9 ^{+1.9} _{-3.1}	82.614673	26.2	-20.2 ^{+1.8} _{-2.1}	180.486860	25.9	-20.2 ^{+1.4} _{-1.7}
72.451377	27.8	-17.7 ^{+1.8} _{-3.2}	82.626794	16.6	-16.7 ^{+3.3} _{-1.7}			

Notes. The signal-to-noise ratio (S/N) in Tables A.1 to A.13 is calculated as the median signal over the measured scatter of a continuum region close to 5500 Å.

Table A.2. KOI-0131: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
111.576836	7.0	-6.2 ^{+1.7} _{-1.4}	120.636824	6.5	-5.3 ^{+3.1} _{-3.4}	497.517894	4.2	-8.7 ^{+4.4} _{-8.8}
115.458790	9.1	-7.8 ^{+1.6} _{-1.1}	418.567422	6.5	-12.1 ^{+9.3} _{-2.2}	514.364588	4.6	-8.1 ^{+8.9} _{-2.2}
115.493531	7.4	-10.7 ^{+2.8} _{-2.3}	418.599802	7.6	-11.8 ^{+2.8} _{-0.11}	514.401807	11.2	-21.5 ^{+5.3} _{-2.9}
115.493595	14.0	-11.6 ^{+4.4} _{-1.8}	418.632175	12.2	-10.5 ^{+2.9} _{-4.8}	514.402164	7.0	-8.7 ^{+2.1} _{-2.8}
115.528462	8.0	-8.1 ^{+2.4} _{-2.0}	436.501911	7.1	159.32 ^{+0.12} _{-4.4}	514.438668	5.2	3.3 ^{+6.2} _{-3.6}
119.544606	4.5	-8.4 ^{+2.6} _{-1.3}	436.538388	6.5	0.0 ^{+4.8} _{-5.1}	529.484818	8.7	-12.1 ^{+4.0} _{-2.3}
120.530916	7.0	-8.7 ^{+1.4} _{-3.3}	436.573185	5.2	-10.0 ^{+4.7} _{-2.6}	529.521132	12.7	-13.4 ^{+2.6} _{-4.0}
120.566218	6.2	-5.0 ^{+4.1} _{-3.0}	497.439970	5.2	-3.5 ^{+6.5} _{-4.2}	529.521166	7.2	-6.1 ^{+3.4} _{-1.1}
120.583937	13.4	-7.9 ^{+2.9} _{-2.9}	497.475725	6.2	-5.3 ^{+3.1} _{-1.1}	529.557411	4.5	-12.9 ^{+3.4} _{-1.8}
120.601789	6.2	-8.5 ^{+3.2} _{-4.6}	497.477863	9.5	-11.4 ^{+5.0} _{-2.5}			

Table A.3. KOI-0340: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian Date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian Date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
111.395672	13.8	-103.499 ^{+0.045} _{-0.045}	116.633232	9.5	-72.401 ^{+0.074} _{-0.057}	127.489427	15.8	-83.806 ^{+0.063} _{-0.058}
111.431211	12.8	-103.559 ^{+0.095} _{-0.095}	119.579846	11.6	-73.268 ^{+0.059} _{-0.061}	133.386589	12.5	-97.467 ^{+0.069} _{-0.071}
113.605011	12.5	-91.229 ^{+0.075} _{-0.075}	119.612757	19.6	-73.172 ^{+0.055} _{-0.054}	133.404004	15.2	-97.457 ^{+0.085} _{-0.074}
113.621494	17.8	-91.001 ^{+0.071} _{-0.058}	119.614455	12.4	-73.262 ^{+0.057} _{-0.063}	133.421419	8.1	-97.52 ^{+0.10} _{-0.055}
113.637977	12.5	-90.909 ^{+0.058} _{-0.082}	119.643968	9.2	-73.381 ^{+0.061} _{-0.069}	137.604302	9.5	-86.483 ^{+0.048} _{-0.056}
116.598403	7.8	-72.213 ^{+0.082} _{-0.074}	127.454588	15.5	-83.850 ^{+0.054} _{-0.10}	137.621876	14.1	-86.268 ^{+0.050} _{-0.085}
116.615818	12.6	-72.333 ^{+0.074} _{-0.059}	127.472007	21.9	-83.789 ^{+0.056} _{-0.048}	137.639450	9.9	-86.171 ^{+0.058} _{-0.050}

Table A.4. KOI-0366: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian Date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
66.494606	15.4	6.8 ^{+1.2} _{-1.0}	82.469641	15.4	8.3 ^{+1.3} _{-0.41}	112.644079	15.4	7.45 ^{+0.52} _{-0.46}
69.490469	15.4	7.7 ^{+1.8} _{-1.6}	82.487003	15.4	7.94 ^{+0.78} _{-0.39}	118.374379	15.4	8.19 ^{+0.47} _{-0.31}
71.558576	15.4	7.85 ^{+0.37} _{-0.28}	82.504365	15.4	7.77 ^{+0.84} _{-0.25}	118.398555	15.4	8.79 ^{+0.40} _{-0.24}
71.570735	15.4	7.15 ^{+0.38} _{-0.31}	92.591566	15.4	9.07 ^{+0.40} _{-0.53}	118.398689	15.4	9.00 ^{+0.29} _{-0.53}
71.582894	15.4	7.50 ^{+0.40} _{-0.27}	92.615777	15.4	9.11 ^{+0.38} _{-0.71}	118.423132	15.4	8.06 ^{+0.38} _{-0.33}
72.599880	15.4	9.06 ^{+0.32} _{-0.30}	92.615814	15.4	9.06 ^{+0.33} _{-0.30}	126.369758	15.4	7.87 ^{+0.51} _{-0.61}
72.612031	15.4	8.80 ^{+0.31} _{-0.77}	92.640099	15.4	8.93 ^{+0.44} _{-0.45}	126.382150	15.4	7.93 ^{+0.55} _{-0.28}
72.624182	15.4	8.37 ^{+0.36} _{-0.72}	101.543893	15.4	7.17 ^{+0.44} _{-0.41}	126.394542	15.4	9.36 ^{+0.64} _{-0.26}
76.440887	15.4	9.00 ^{+0.93} _{-0.42}	101.561229	15.4	8.64 ^{+0.34} _{-0.34}	130.380236	15.4	7.95 ^{+0.36} _{-0.51}
76.466954	15.4	9.54 ^{+0.65} _{-0.46}	101.578566	15.4	8.69 ^{+0.30} _{-0.30}	130.392427	15.4	8.29 ^{+0.31} _{-0.42}
76.467735	15.4	9.95 ^{+0.88} _{-0.29}	110.385278	15.4	7.93 ^{+0.62} _{-0.39}	130.404619	15.4	9.46 ^{+0.32} _{-0.24}
76.492240	15.4	8.27 ^{+0.50} _{-1.1}	110.397526	15.4	7.46 ^{+0.65} _{-0.56}	139.381895	15.4	7.75 ^{+0.57} _{-0.51}
79.543631	15.4	9.61 ^{+0.55} _{-0.68}	110.409774	15.4	7.57 ^{+0.88} _{-0.32}	139.394228	15.4	8.35 ^{+0.51} _{-0.25}
79.555913	15.4	8.67 ^{+0.39} _{-0.32}	112.619832	15.4	8.67 ^{+0.34} _{-0.27}	139.406562	15.4	8.41 ^{+0.53} _{-0.44}
79.568194	15.4	8.59 ^{+0.34} _{-0.33}	112.631955	15.4	7.36 ^{+0.49} _{-0.47}			

Table A.5. KOI-0371: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
121.454974	11.8	-65.169 ^{+0.052} _{-0.052}	505.601217	6.5	-53.219 ^{+0.049} _{-0.053}	803.627383	9.6	-65.601 ^{+0.055} _{-0.059}
121.467317	17.7	-65.138 ^{+0.049} _{-0.053}	505.612199	9.8	-53.152 ^{+0.049} _{-0.059}	824.620384	5.5	-64.962 ^{+0.067} _{-0.048}
121.479659	13.2	-65.200 ^{+0.053} _{-0.061}	505.623181	7.5	-52.957 ^{+0.058} _{-0.059}	824.642337	5.2	-64.965 ^{+0.070} _{-0.049}
436.604913	13.7	-58.579 ^{+0.061} _{-0.068}	528.419975	10.2	-53.651 ^{+0.053} _{-0.049}	838.397849	9.2	-64.515 ^{+0.066} _{-0.053}
436.629188	13.7	-58.399 ^{+0.068} _{-0.054}	528.438254	18.5	-53.526 ^{+0.054} _{-0.050}	838.416113	14.1	-64.386 ^{+0.062} _{-0.049}
497.381256	9.6	-53.264 ^{+0.054} _{-0.053}	528.456533	15.7	-53.573 ^{+0.059} _{-0.055}	838.434376	10.2	-64.406 ^{+0.051} _{-0.054}
497.394856	15.2	-53.194 ^{+0.053} _{-0.072}	559.495749	11.7	-58.079 ^{+0.059} _{-0.067}	843.450061	11.3	-64.246 ^{+0.059} _{-0.048}
497.408455	10.8	-52.975 ^{+0.053} _{-0.060}	560.496212	14.5	-58.283 ^{+0.049} _{-0.070}	843.466246	16.1	-64.224 ^{+0.053} _{-0.062}
500.645274	5.6	-52.852 ^{+0.072} _{-0.049}	803.605301	9.3	-65.603 ^{+0.050} _{-0.066}	843.482431	11.2	-64.270 ^{+0.048} _{-0.053}
500.669675	9.0	-53.041 ^{+0.060} _{-0.058}	803.616342	13.5	-65.618 ^{+0.048} _{-0.051}			

Table A.6. KOI-0625: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
71.489198	11.6	-25.97 ^{+0.55} _{-0.45}	88.573506	1.7	-28.8 ^{+4.2} _{-0.89}	94.589328	9.8	-25.77 ^{+0.98} _{-1.6}
71.506591	16.5	-25.80 ^{+0.62} _{-0.59}	88.592027	9.8	-26.27 ^{+0.74} _{-0.67}	102.432371	9.3	-24.9 ^{+1.1} _{-0.56}
71.523984	11.6	-26.13 ^{+0.65} _{-0.64}	88.597524	13.0	-23.8 ^{+1.9} _{-0.99}	102.469438	9.1	-26.92 ^{+0.99} _{-0.54}
72.496141	10.7	-26.39 ^{+0.79} _{-1.1}	88.627038	7.8	-24.6 ^{+1.7} _{-1.8}	102.469462	15.6	-31.2 ^{+2.5} _{-0.72}
72.513475	15.2	-25.29 ^{+0.84} _{-0.55}	91.459181	8.3	-25.9 ^{+1.4} _{-0.85}	102.506577	7.8	-24.3 ^{+1.8} _{-0.45}
72.530808	10.7	-25.5 ^{+1.3} _{-0.49}	91.493991	15.7	-25.1 ^{+1.3} _{-0.75}	121.559629	8.1	-25.2 ^{+1.1} _{-0.73}
77.443828	11.6	-25.57 ^{+0.69} _{-0.89}	91.494063	9.0	-26.1 ^{+1.2} _{-0.84}	121.594577	13.7	-24.1 ^{+1.2} _{-3.8}
77.462844	16.5	-26.31 ^{+0.59} _{-0.62}	91.528730	9.5	-26.64 ^{+0.95} _{-0.90}	121.594628	7.6	-26.5 ^{+1.6} _{-2.3}
77.481860	11.8	-26.66 ^{+0.65} _{-5.3}	92.525138	11.2	-25.37 ^{+0.91} _{-0.95}	121.629474	7.8	-24.7 ^{+1.3} _{-1.9}
79.476176	9.0	-25.5 ^{+1.1} _{-0.92}	92.542705	16.1	-26.08 ^{+0.97} _{-1.9}	127.526771	9.7	-25.03 ^{+0.99} _{-1.1}
79.493735	14.0	-27.39 ^{+0.96} _{-3.5}	92.560272	10.9	-25.77 ^{+0.86} _{-1.1}	127.561701	9.0	-26.1 ^{+1.0} _{-1.1}
79.511293	10.4	-25.08 ^{+0.63} _{-2.4}	93.453444	10.2	-25.0 ^{+1.2} _{-1.4}	127.561732	16.5	-25.92 ^{+0.89} _{-1.9}
80.462852	8.2	-29.7 ^{+5.4} _{-3.5}	93.471006	14.6	-24.2 ^{+1.7} _{-1.2}	127.596724	8.9	-26.22 ^{+0.61} _{-0.92}
80.487557	13.2	-23.6 ^{+4.4} _{-0.62}	93.488568	10.3	-27.6 ^{+1.7} _{-1.0}	137.461469	8.5	-25.1 ^{+1.1} _{-2.4}
80.512261	10.1	-25.4 ^{+1.0} _{-1.4}	94.519592	10.9	-26.06 ^{+0.94} _{-0.85}	137.497308	7.9	-23.3 ^{+1.9} _{-1.3}
87.567872	7.5	-25.5 ^{+4.1} _{-1.2}	94.554529	18.6	-25.0 ^{+1.1} _{-0.41}	137.498740	15.2	-27.1 ^{+1.9} _{-0.72}
87.585564	10.0	-25.7 ^{+2.8} _{-0.95}	94.554666	10.3	-25.29 ^{+0.89} _{-1.1}	137.537443	9.5	-26.52 ^{+0.64} _{-1.00}
87.603257	6.2	-24.7 ^{+2.7} _{-0.71}						

Table A.7. KOI-0686: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
91.564471	9.5	-29.153 ^{+0.081} _{-0.081}	110.542846	7.5	-34.89 ^{+0.12} _{-0.093}	124.524128	6.5	-34.625 ^{+0.075} _{-0.069}
91.581828	13.9	-29.146 ^{+0.085} _{-0.082}	110.560305	11.0	-34.77 ^{+0.11} _{-0.061}	129.435272	10.8	-33.343 ^{+0.081} _{-0.085}
91.599185	7.0	-29.397 ^{+0.082} _{-0.073}	110.577764	6.4	-35.15 ^{+0.11} _{-0.075}	130.540005	10.0	-33.237 ^{+0.076} _{-0.060}
100.433076	8.2	-24.792 ^{+0.073} _{-0.067}	124.453660	6.9	-34.620 ^{+0.093} _{-0.081}	130.574986	18.8	-33.098 ^{+0.077} _{-0.11}
100.468077	16.2	-24.749 ^{+0.060} _{-0.066}	124.488780	8.2	-34.500 ^{+0.061} _{-0.076}	130.575012	11.1	-33.291 ^{+0.077} _{-0.068}
100.468144	9.7	-24.886 ^{+0.067} _{-0.12}	124.488856	13.1	-34.515 ^{+0.068} _{-0.077}	130.609940	10.6	-33.159 ^{+0.069} _{-0.077}
100.503013	9.5	-24.834 ^{+0.066} _{-0.11}						

Table A.8. KOI-0972: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
100.376405	58.2	-8.2 ^{+4.2} _{-3.4}	114.503592	53.2	-8.5 ^{+8.7} _{-4.4}	126.348892	37.8	-8.8 ^{+3.3} _{-3.5}
100.388716	86.3	-12.9 ^{+3.4} _{-2.6}	114.651427	40.6	-10.0 ^{+3.2} _{-5.5}	127.358229	47.4	-11.2 ^{+4.6} _{-5.1}
100.401026	64.0	-15.4 ^{+3.0} _{-4.0}	115.359156	38.5	-11.3 ^{+5.2} _{-4.3}	128.359248	34.8	-14.9 ^{+8.8} _{-4.7}
101.610586	41.2	-12.8 ^{+4.5} _{-4.8}	115.507564	44.8	-14.1 ^{+3.8} _{-5.1}	129.361016	37.8	-15.5 ^{+3.3} _{-3.7}
101.622675	61.7	-11.7 ^{+4.5} _{-5.8}	115.655973	22.7	-10.7 ^{+5.5} _{-4.1}	130.359776	54.4	-16.1 ^{+4.6} _{-3.3}
101.634765	45.9	-15.4 ^{+5.1} _{-2.5}	116.430815	41.5	-17.0 ^{+4.1} _{-3.0}	131.358377	41.9	-14.1 ^{+3.8} _{-4.4}
102.370604	61.3	-18.8 ^{+6.3} ₋₁₁	117.360460	34.2	-15.8 ^{+5.1} _{-2.7}	132.358859	40.2	-4 ⁺¹¹ ₋₁₄
102.382723	89.3	-9.3 ^{+2.3} _{-4.8}	117.399590	41.8	-13.1 ^{+4.9} _{-5.3}	133.361742	46.1	-14.0 ^{+4.5} _{-0.92}
102.394841	65.1	-7.7 ^{+2.7} _{-4.5}	117.438719	24.0	-14.9 ^{+6.1} _{-3.0}	137.356202	41.2	-22.5 ^{+6.5} ₋₁₆
103.602984	62.3	-13.2 ^{+8.8} _{-5.1}	118.353116	34.0	-18.9 ^{+5.4} _{-2.9}	138.359861	43.1	-19.0 ^{+5.4} ₋₁₅
103.615092	87.4	-16.4 ^{+6.6} _{-4.8}	119.361354	23.1	-18.7 ^{+5.7} _{-3.0}	140.360137	37.0	-7.7 ^{+5.0} _{-2.8}
103.627200	61.2	-10.7 ^{+5.7} _{-4.8}	120.384560	29.7	-22.0 ^{+4.6} _{-3.7}	141.354705	39.0	-16.0 ^{+4.2} _{-3.6}
110.363523	34.3	-13.4 ^{+6.5} _{-4.2}	121.363682	40.7	-16.2 ^{+3.5} _{-8.6}	418.660632	37.0	-15.0 ^{+4.7} _{-1.9}
111.366741	39.7	-15.0 ^{+5.2} _{-2.5}	122.427018	41.9	-13.0 ^{+3.4} _{-3.1}	420.646028	15.4	-27 ⁺²⁰ _{-5.9}
112.358116	48.0	-12.2 ^{+5.3} _{-4.6}	123.355871	30.5	-6.7 ^{+6.6} _{-4.1}	420.658684	21.2	-82.22 ^{+0.97} ₋₃₇
113.357987	34.7	-6.4 ^{+5.9} _{-4.8}	124.352637	41.6	-14.2 ^{+3.9} _{-3.3}	426.552329	13.7	6 ⁺¹⁶ _{-3.1}
114.355757	34.3	-11.8 ^{+5.3} _{-3.7}	125.446545	41.2	-12.2 ^{+3.5} _{-8.5}	435.646207	34.0	4 ⁺¹² _{-4.2}

Table A.9. KOI-1463: measured radial velocities

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
114.381820	12.8	-30.76 ^{+0.47} _{-0.47}	517.458750	13.2	31.76 ^{+0.28} _{-0.41}	838.477732	12.2	306.20 ^{+0.33} _{-0.39}
114.399160	19.8	-30.93 ^{+0.39} _{-0.36}	805.527896	7.3	305.37 ^{+0.34} _{-0.34}	838.494471	16.1	305.52 ^{+0.29} _{-0.19}
114.416499	15.2	-31.11 ^{+0.36} _{-0.17}	805.560558	3.2	306.09 ^{+0.41} _{-0.33}	838.511211	8.9	305.54 ^{+0.31} _{-0.34}
517.378382	14.5	31.18 ^{+0.17} _{-0.28}	805.560620	11.3	305.58 ^{+0.34} _{-0.31}	841.587718	6.9	305.43 ^{+0.29} _{-0.29}
517.418566	20.1	31.36 ^{+0.19} _{-0.34}	805.593404	7.5	305.57 ^{+0.34} _{-0.29}			

Table A.10. KOI-3725: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
500.625109	14.2	-51.3 ^{+3.9} _{-2.1}	504.571903	29.6	-30.9 ^{+1.2} _{-0.97}	841.530484	14.6	-15.0 ^{+2.1} _{-1.5}
501.383460	19.2	-46.2 ^{+2.0} _{-1.4}	504.609225	22.8	-41.9 ^{+1.1} _{-0.73}	841.536254	20.6	-29.0 ^{+2.7} _{-1.1}
503.425012	23.2	-42.1 ^{+1.4} _{-1.3}	517.650133	21.0	-45.20 ^{+0.79} _{-1.3}	841.542025	14.2	-29.1 ^{+1.4} _{-2.9}
504.534581	19.0	-50.2 ^{+1.4} _{-1.2}						

Table A.11. KOI-3728: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
354.369018	10.1	-36.3 ^{+5.3} _{-3.4}	511.418066	9.2	-44 ⁺¹⁰ _{-3.6}	523.540289	15.3	-48.6 ^{+3.2} _{-1.9}
354.379993	14.7	-37.0 ^{+3.8} _{-2.5}	512.472273	6.9	-54 ⁺¹¹ _{-2.5}	525.518022	14.4	-47.9 ^{+4.7} _{-2.7}
354.390968	10.1	-34.5 ^{+5.3} ₋₁₆	513.408866	11.6	-48.6 ^{+5.6} _{-3.0}	525.536150	20.8	-55.7 ^{+4.6} ₋₂₆
498.570987	12.2	-57.8 ^{+4.4} ₋₂₅	513.427128	18.5	-50.7 ^{+5.0} _{-2.2}	525.554278	14.8	-53.9 ^{+5.4} _{-2.6}
498.583268	16.9	-58.4 ^{+3.1} ₋₁₅	513.445391	13.7	-50.9 ^{+6.0} _{-6.9}	528.567258	11.1	-45.1 ^{+4.2} ₋₁₁
498.595550	11.5	-58.3 ^{+2.9} ₋₁₇	514.605639	14.4	-56.9 ^{+5.2} _{-4.3}	559.339189	16.7	-57.0 ^{+3.7} _{-2.5}
500.576958	4.8	-30 ⁺²⁰ ₋₃₅	514.623762	20.1	-49 ⁺¹⁰ _{-3.3}	559.371563	15.8	-57.1 ^{+2.0} _{-3.9}
500.602103	6.8	-67 ⁺²⁵ _{-3.6}	514.641885	14.0	-59.8 ^{+7.4} _{-4.5}	559.403933	14.8	-53.7 ^{+5.5} _{-6.7}
501.428000	3.9	-49 ⁺¹⁷ _{-8.2}	517.590081	14.0	-45.7 ^{+4.9} _{-6.4}	567.330058	14.7	-50.1 ^{+2.6} _{-4.8}
510.446736	6.1	-51 ⁺¹⁹ _{-9.7}	517.606266	18.5	-48.7 ^{+5.6} _{-3.1}	567.367052	15.0	-47.4 ^{+2.5} _{-3.2}
510.468900	8.9	-51 ⁺¹⁵ _{-4.4}	517.622450	11.4	-50.4 ^{+4.0} _{-1.4}	567.403480	14.6	-50.2 ^{+3.2} _{-3.8}
510.491065	6.8	-24 ⁺²⁸ _{-5.7}	523.503712	13.5	-47.3 ^{+3.7} _{-5.6}	597.418633	12.6	-48 ⁺²⁵ _{-3.2}
511.390550	11.0	-53.3 ^{+4.5} _{-4.9}	523.522001	20.9	-49.4 ^{+4.7} _{-2.2}	597.418633	9.3	-47 ⁺¹⁴ ₋₇₆
511.404308	14.7	-56.3 ^{+4.0} _{-5.7}						

Table A.12. KOI-3853: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
498.550774	19.3	-88.037 ^{+0.040} _{-0.040}	511.624458	11.8	-57.982 ^{+0.054} _{-0.070}	528.494410	28.8	-59.539 ^{+0.052} _{-0.049}
500.427256	6.8	-78.182 ^{+0.051} _{-0.051}	511.656257	9.6	-57.901 ^{+0.070} _{-0.057}	528.515065	43.6	-59.420 ^{+0.053} _{-0.047}
503.522251	23.8	-67.622 ^{+0.057} _{-0.057}	513.591688	26.4	-70.695 ^{+0.057} _{-0.058}	528.535719	32.7	-59.298 ^{+0.054} _{-0.053}
504.628523	24.9	-64.491 ^{+0.053} _{-0.053}	515.538671	25.8	-101.989 ^{+0.058} _{-0.053}	559.438923	28.5	-108.981 ^{+0.049} _{-0.057}
505.425120	25.4	-62.606 ^{+0.048} _{-0.048}	522.559858	24.5	-76.193 ^{+0.053} _{-0.050}	559.449900	39.6	-108.981 ^{+0.048} _{-0.056}
510.419882	21.0	-56.134 ^{+0.052} _{-0.052}	526.420908	35.1	-64.086 ^{+0.050} _{-0.048}	559.460877	27.4	-109.009 ^{+0.047} _{-0.048}
511.363906	25.3	-57.187 ^{+0.051} _{-0.051}	526.439128	45.2	-64.033 ^{+0.048} _{-0.052}	569.430575	25.6	-64.360 ^{+0.053} _{-0.053}
511.553563	33.1	-57.133 ^{+0.056} _{-0.056}	526.457348	27.8	-63.921 ^{+0.048} _{-0.054}	569.467568	16.5	-64.290 ^{+0.057} _{-0.048}
511.569631	14.5	-57.611 ^{+0.056} _{-0.054}						

Table A.13. KOI-3890: measured radial velocities.

Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)	Julian Date (days)-2 456 000	$\overline{S/N}$	RV (km s ⁻¹)
499.397905	6.7	-27.368 ^{+0.087} _{-0.087}	511.496364	2.8	-26.35 ^{+0.16} _{-0.074}	516.552987	9.4	-25.955 ^{+0.073} _{-0.38}
499.438485	4.1	-27.74 ^{+0.19} _{-0.19}	511.535899	5.5	-26.176 ^{+0.074} _{-0.052}	516.554295	16.9	-25.835 ^{+0.064} _{-0.098}
502.629346	6.2	-27.330 ^{+0.072} _{-0.072}	513.484972	7.6	-26.418 ^{+0.052} _{-0.072}	516.589283	10.0	-25.870 ^{+0.066} _{-0.070}
510.526583	5.0	-26.60 ^{+0.10} _{-0.100}	513.522807	14.2	-26.240 ^{+0.055} _{-0.056}	522.447180	3.2	-24.71 ^{+0.38} _{-0.090}
510.564787	2.5	-26.35 ^{+0.24} _{-0.24}	513.523404	8.2	-26.140 ^{+0.072} _{-0.065}	522.485030	12.2	-24.798 ^{+0.096} _{-0.055}
510.577098	8.2	-26.391 ^{+0.090} _{-0.074}	513.560045	8.5	-26.260 ^{+0.056} _{-0.073}	522.485601	7.2	-24.970 ^{+0.098} _{-0.064}
510.639922	7.1	-26.387 ^{+0.074} _{-0.082}	516.520616	9.8	-25.942 ^{+0.065} _{-0.066}	522.522308	8.8	-25.041 ^{+0.070} _{-0.096}
511.457622	8.2	-26.370 ^{+0.082} _{-0.16}						