Multiplicity in transiting planet-host stars

A lucky imaging study of *Kepler* candidates

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ABSTRACT

Context. In the exoplanetary era, the *Kepler* spacecraft is causing a revolution by discovering thousands of new planet candidates. However, a follow-up program is needed to reject false candidates and fully characterize the bona-fide exoplanets.

Aims. Our main aims are to 1./ detect and analyze close companions inside the typical *Kepler* point spread function (PSF) to study whether they are the responsible for the dimming found in *Kepler* light curves, 2./ study the change in the stellar and planetary parameters caused by an unresolved object, 3./ help validate the *Kepler* objects of interest (KOI) that do not have any object inside the *Kepler* PSF, and 4./ study the multiplicity rate of planet-host candidates. Such a large sample of observed planet-host candidates allows us to derive statistics for close (visual or bounded) companions to the harboring star.

Methods. We present lucky imaging observations for a total of 98 KOIs. This technique is based on the acquisition of thousands of very-short-exposure-time images. A selection and combination of a small amount of the highest quality frames provides a high resolution image with objects having a 0.1 arcsec PSF. We apply this technique to carry out observations in the Sloan *i* and *z* filters of our *Kepler* candidates.

Results. We find blended objects inside the *Kepler* PSF for a significant percentage of KOIs. On the one hand, only 58.2% of the hosts do not have any object within 6 arcsec. On the other hand, we find 19 companions closer than 3 arcsec in 17 KOIs. According to their magnitudes and *i* – *z* colors, 8 of them could be physically bound to the host star.

Key words. binaries: visual – instrumentation: high angular resolution – planets and satellites: fundamental parameters

1. Introduction

It is not so long since the first discoveries of extrasolar planets. However, after the first detection of an exoplanet orbiting a main-sequence star (Mayor & Queloz 1995; Marcy & Butler 1996), the scientific community has discovered and confirmed hundreds of these objects around other stars. In this context, the *Kepler* Space Telescope has detected a large sample of new planet-host candidates by continuously observing more than 150 000 stars in a specific field of view (RA = 19h22m40s Dec = +44°30'00"). During the first five quarters of observations (i.e., ≈4.5 months), the *Kepler* team collected in its second public release a total amount of 997 planet-host star candidates (second public release, Borucki et al. 2011).

However, to date, fewer than 5% of these candidates have been confirmed. After the candidate selection, there is a mandatory step to reject false positives before attempting any highly accurate (difficult and expensive) radial velocity measurements. Since the *Kepler* effective point-spread function (PSF) is very large (6–10 arcsec, depending on the particular target) and its pixel size is about 4 arcsec, several background objects could be blended with the host candidate (called *Kepler* object of interest, hereafter KOI). Bounded or not, these objects clearly affect the star and planet parameters such as the planet-to-star radius (R_p/R_*), semi-major axis (a/R_*), impact parameter (b), and even the planetary mass (M_p).

The presence of a secondary star could lead, for example, to the definite rejection of the candidate (see O'Donovan et al. 2006). There are several configurations that can mimic an

exoplanet transit around its host star. The most relevant are A./ a small substellar object transiting the other component of the binary system, since the smallest stars and brown dwarfs have the same size as Jupiter; B./ a stellar binary blended with a background star; C./ a grazing binary, which has not been ruled out by additional photometry or spectroscopy; D./ a background eclipsing binary blended by the light of the KOI; E./ a larger planet transiting a background star blended by the main target (would not strictly be a false positive since there is a planet in the system but would be in the sense that it rejects the brightest central star as a planet-host); and F./ a long-term spot. There would be a “G-case” where the main target actually hosts a planet but with either a blended background companion or a non-transiting bounded companion. These configurations would lead to a change in the planet properties, as we said before.

Some of these configurations might be ruled out by the automatic pipeline implemented by the *Kepler* team (Jenkins et al. 2010). While cases A and B are clearly rejected by this pipeline and an individual study of the light curves done by the team itself (Borucki et al. 2011), low-resolution spectroscopy clearly reject the C configuration. However, the D, E, and G cases are the main sources of false positives in the sample of transiting planet candidates. More specifically, case G clearly shows the need for an intense high-resolution imaging follow-up program to validate the planetary nature of the transients. Owing to the *Kepler* long base-line, we expect few or no F cases.

Theoretical studies of the false positive probability of *Kepler* candidates conclude that obtaining high resolution images down to 1–2 arcsec is crucial for confirming the planetary detections

and their physical properties. As an example, an Earth-size planet transiting a faint star might have a false positive probability greater than 20% if it lacks high resolution imaging, which could potentially be decreased to less than 2% with a high resolution image (Morton & Johnson 2011). Several authors have acquired this kind of observation for other planet-host candidates finding significantly different planet-star properties. For instance, Daemgen et al. (2009) found stellar companions to three stars harboring planets. As a consequence, the updated values of the physical parameters differ by about 2% from the previous ones.

However, even if the planet is confirmed, its formation and evolution scenarios (including its migration) require an accurate description of the effect of bounded stellar companions. The vast majority of planets found in multiple systems are actually S-type (the planet orbits one of the two components of the system, and the other component plays the role of a gravitational perturber, see Kley 2010). These secondary objects make planet formation difficult since they interact dynamically with the system elements producing an extra heating of the protoplanetary disk. All of these factors may cause large changes in the planetary architecture and exoplanetary properties from those present when the planets formed around single stars. For instance, Eggenberger et al. (2004) found a statistical segregation in the planet mass for planets with orbital periods shorter than 40 days around single and multiple systems.

In this paper, we present the first statistical study of multiplicity in *Kepler* exoplanetary candidates. A set of high resolution images obtained with the lucky imaging technique (Law et al. 2006) at the 2.2 m telescope in Calar Alto Observatory (Almería, Spain) with the AstraLux instrument was acquired. This technique allows us to obtain diffraction-limited observations with the best seeing conditions in the Sloan Digital Sky Survey (SDSS) *i* band (see Félix Hormuth's Ph.D. dissertation). A total of 98 KOIs (i.e., about 10% of the candidates listed in the second public release of the *Kepler* team) have been targeted and studied.

In Sect. 2, we explain the observations, image processing, and data extraction from the raw images, in terms of sample selection (Sect. 2.1), data acquisition (Sect. 2.2), data reduction, and photometric calibration (Sect. 2.3), including the astrometric corrections, and a study of the sensitivity curves and detectability of our observations. The results based on these observations are presented in Sect. 3. We also perform spectral typing of the detected companions (Sect. 4.1) and investigate the possible gravitational bound between some of them (Sect. 4.2). In Sect. 4.3, we discuss the implications of the calculated planetary parameters from the *Kepler* light curves for the possible presence of a blended star. Some particularly interesting cases are studied in Sect. 4.4 and the final conclusions of this work are presented in Sect. 5.

2. Observations and data reduction

2.1. Sample selection

We observed 98 KOIs. Owing to the lack of any kind of follow-up observations the majority of them were selected from the published data of the *Kepler* team (Borucki et al. 2011, second public release). The selection of the rest was coordinated with the *Kepler* team. In addition, we limited our targets to be brighter than 15 mag in the Sloan *i* band in order to detect objects 5 mag fainter than the KOI (see Sect. 2.3.6). Apart from these

constraints, KOIs were randomly selected from the remaining sample so we expect no bias in our results.

2.2. Data acquisition

The data presented in this paper were taken at the Calar Alto Observatory (Almería, Spain) during 19 nights of observations divided into three separate runs (6–12 June 2011, 1–10 July 2011, and 25–26 July 2011). Although two nights were lost owing to adverse weather conditions, the remaining 17 had very good atmospheric stability with low atmospheric extinction and either sporadic or absent clouds, which are ideal for this observing technique. The mean natural seeing was around 0.9 arcsec over the entire run.

We used the AstraLux instrument placed at the 2.2 m telescope to perform diffraction-limited imaging of our sample of KOIs with the lucky imaging technique. We used the entire available field of view of the camera (i.e., 24×24 arcsec) to cover a separation range encompassing the entire mean *Kepler* PSF (6–10 arcsec). In brief, we took thousands of images with short exposure times (100–200 ms), well below the typical timescale on which the atmospheric turbulence changes (see Felix Hormuth's Ph.D. dissertation). We set the exposure times and number of frames according to the atmospheric conditions and target magnitude in order to reach at least 5.0 mag fainter than the central KOI. Thus, our total exposure times were in the range 340–2000 s. We note that objects fainter than this magnitude difference would not affect the planet-star properties by more than 0.5% in the case of the R_p/R_* rate (see Eq. (6) in Seager & Mallén-Ornelas 2003). Moreover, the probability that *Kepler* observations have detected a transit with a signal-to-noise ratio (S/N) greater than 7.1 decreases as the star gets fainter. Thus, we designed our observations to reach $\Delta m_i \approx 5.0$ mag 1.0–1.5 arcsec from the KOI.

Images were firstly obtained in the SDSS *i* filter since the PSF deformation is lower for this band than for shorter wavelengths (this result is quite similar for the SDSS *z* band). An on-the-fly reduction allowed us to immediately check for close sources. If any were present, SDSS *z* band images were acquired in order to characterize the secondary object by using its *i* – *z* color (see Sect. 2.3.5).

2.3. Data reduction and photometric calibration

2.3.1. Basic reduction

We used the AstraLux pipeline (see Hormuth 2007)¹ to perform the basic reduction and combination of our lucky imaging frames. First, this pipeline applies the bias and flat-field correction corresponding to each night of the science images. We used the dome flat-field to avoid inhomogeneities due to the passing of some clouds during sunset for most of the observing nights. Second, it measures the quality of each science frame to select the 1.0%, 2.5%, 5.0%, and 10% frames with the highest Strehl ratios (Strehl 1902), calculates the shifts between these single frames, performs the stacking, and divides the pixel size in half (i.e., the pixel scale is resampled from 0.0466''/pixel to 0.0233''/pixel). According to our observing configuration (number of frames, single exposure time, and gain), we need to use the 10% selection-rate images to reduce the photometric errors (as recommended in the user's manual). Inspection of the lower

¹ <http://www.mpia-hd.mpg.de/ASTRALUX/>

Table 1. Plate solution for our photometric observations.

Coeff.	ξ	η
c_{10}	-23.58 mas/px	-0.65 mas/px
c_{01}	-0.81 mas/px	23.58 mas/px
c_{20}	$4.05 \times 10^{-3} \text{ mas/px}^2$	$7.93 \times 10^{-5} \text{ mas/px}^2$
c_{02}	$1.31 \times 10^{-3} \text{ mas/px}^2$	$9.35 \times 10^{-5} \text{ mas/px}^2$
rms	48.5 mas	34.5 mas
PA	1.78°	
Pixel scale	23.59 mas/px	

selection-rate images was done for source detection purposes but not for the photometric analysis presented in this paper.

2.3.2. Astrometric corrections

Astrometric corrections were applied to the positions of the targets when calculating angular separations and angles between them. We made use of our observations of the M 15 dense globular cluster. A total of 66 stars in our image were identified and matched with the Yanny et al. (1994) catalog from images of the *Hubble* Space Telescope. We performed an astrometric calibration using the *ccmap* package in IRAF. We computed the transformation between $[x, y]$ coordinates to the $[\xi, \eta]$ tangent plane coordinates in a second order fitting

$$\xi = c_{00} + c_{10}x + c_{01}y + c_{20}x^2 + c_{02}y^2 \quad (1)$$

$$\eta = c'_{00} + c'_{10}x + c'_{01}y + c'_{20}x^2 + c'_{02}y^2, \quad (2)$$

where c_{ij} are the corresponding calculated coefficients, which are shown in Table 1. We found residuals of 48.5 mas in the ξ direction and 34.5 mas in the η direction. The pixel scale and rotation angle were found to be $0.02359 \pm 0.0005 \text{ arcsec/pixel}$ and $1.78 \pm 0.01 \text{ degrees}$, respectively. We considered the rms value as our mean astrometric error in both tangential coordinates.

2.3.3. Source detection and photometric extraction

The SExtractor software for source extraction (Bertin & Arnouts 1996) was used to extract the pseudo-instrumental photometry (explained below) of sources surrounding each KOI. We chose 60 pixel apertures (1.4 arcsec) to account for the maximum flux percentage of the objects. We set the detection threshold to 2.0σ in a minimum area of 30 pixels. Since this software does not take into account the exposure time and electromagnetic gain of the observations, we had to correct the SExtractor output to obtain the real instrumental magnitudes. The gain correction was necessary since different gains were set to different objects to avoid detector saturation. This was the case for standard stars for which we set the software gain to be within 230–255. For all the science images, we applied a software gain of 255, which we note, however, is neither equal nor linearly correlated to the physical electron gain (see Fig. 3.7 of Hormuth 2007). In a private communication, the PI of the instrument (Felix Hormuth) provided us with a calibrated function relating both parameters. Hence, referring to the physical electron gain as Y , the instrumental magnitude of an object would be: $m_{\text{inst}} = m_{\text{SExtractor}} + 2.5 \log(Yt_{\text{exp}})$.

2.3.4. Atmospheric extinction and zero point calculation

The extinction correction and determination of the zero points were done by using observations of SDSS standard stars (Smith et al. 2002). We observed Ross 711 and SA105-815 during the first run; Ross 711, SA105-815 and BD+25-4655 in the second run, and Ross 711 and BD+25-4655 in the third run. A good sampling of the airmass for each night ensured a correct determination of the calibration parameters for the photometric nights, namely the extinction coefficient (χ) and the zero point (C). According to the Calar Alto weather monitoring webpage² and the results of the calibration diagrams ($m_{\text{standard}} - m_{\text{inst}}$ vs. airmass) for each night, we conclude that the following nights of the year 2011 were clearly photometric: July 5, 6, 7, 10, and 26. The average error in the calculated magnitudes for these nights is around 1%. Another set of nights were classified as partially photometric because of sporadic clouds occurring during the observing time or irregular seeing conditions that led to inaccurate photometry, since we observed the standard stars frequently. These nights were June 11 and 12, and July 1, 3, and 9. Consequently, errors in these partially photometric nights are greater (1–3%) but still acceptable for our purposes. The column #5 in Table 5 provide information about the stability of the atmosphere for the observations of each object (according to the acquisition date). From our photometric results, we can conclude that magnitudes brighter than $i = 21$ –22 have negligible errors while fainter objects are too noisy to accurately determine their magnitudes with errors below 1.5% and were then not taken into account for this study.

Hence, the calibrated magnitude for these objects was then calculated to be:

$$m_{\text{cal}} = m_{\text{inst}} + 2.5 \log(A_p Y) + Z_p + C\chi, \quad (3)$$

where A_p is the aperture correction, Y the electron gain, C the extinction coefficient, Z_p the zero point, and χ is the correspondent airmass.

When compared to the *Kepler* Input Catalog (KIC) values provided in the *Kepler* MAST (Mikulski Archive for Space Telescopes)³, we obtain magnitude differences ($i_{\text{KIC}} - i_{\text{AstraLux}}$) smaller than 0.1 mag for around 60% of our objects without close companions, where 90% of them are smaller than 0.4 mag.

2.3.5. Detection and calibration of very close objects

By closely examining the reduced images, we selected the subsample of our KOIs that had close companions within 3 arcsec (17 KOIs) to perform an individual extraction of the photometry. Owing to its proximity to the main target, we would have need to use smaller apertures in order to avoid contamination from the PSF wings of the KOI, hence, an aperture correction was applied. Contamination coming from the KOI's PSF wing was estimated by measuring the amount of flux from the KOI inside the companion's aperture. This extra flux influenced the magnitude of the companion in less than 0.03 mag, which is far smaller than the photometric errors of these sources. Hence, no corrections of this nature were performed in this work. Photometric extraction of the standard stars was also done with the IRAF package⁴ and calibration parameters were re-derived and applied to the science photometry. We determined the aperture correction by using the standard stars. As the *phot* task of the IRAF package already

² Publicly available at www.caha.es/WDXI/wdxi.php

³ <http://archive.stsci.edu/kepler/>

⁴ Image Reduction and Analysis Facility, <http://iraf.noao.edu/>

Fig. 1. Mean completeness and detectability limits of our survey (black solid line) for a 200 s effective exposure-time image. Red dotted line, blue dashed line, and purple dotted-dashed line represent the values for the three photometric nights considered, namely 26 Jul. 11, 05 Jul. 11 and 07 Jul. 11, respectively. Bin size is 0.5 mag. The histograms have been normalized to their maximum value for visualization purposes.

takes into account the exposure time of the image, here we just had to correct for aperture correction, electron gain, and atmospheric extinction. Hence, the final expression for deriving the calibrated magnitudes is

$$m_{\text{cal}} = m_{\text{IRAF}} + 2.5 \log(A_p Y) + Z_p + C_\chi, \quad (4)$$

where χ is the corresponding airmass.

We also tested a PSF approach rather than aperture photometry. The main problem of this technique with lucky-imaging observations is to find a standard PSF for the whole night. Owing to the acquisition technique, each particular image/star would have a characteristic PSF that cannot be modeled by a general one. However, aperture photometry for very close (<1.5 arcsec) and faint companions can involve larger errors even using small apertures. Hence, we decided to use PSF photometry for the 2 KOIs with faint companions at very small angular separations (KOI-1375 and KOI-0387). The PSF was measured for the different available standard stars during the whole night. We calculated the stellar fluxes for each PSF and estimated the relative magnitudes between the KOI and the companion (Δi and Δz) as a weighted average of all values. Since aperture and PSF photometry must coincide for the bright KOI, we used the calibrated photometry for the KOI obtained by aperture photometry (m_p) to obtain the companions' magnitudes as $m_{/C} = m_p + \Delta m$ for each filter in these two cases. For the remaining objects, we used aperture photometry.

2.3.6. Sensitivity, detectability, and limiting magnitudes

We estimated the mean completeness and limiting magnitudes of our images by using the observations of the globular cluster M 15 in order to have a large sample of stars with a wide range of magnitudes. We measured the number of objects per magnitude bin of 0.5 mag on every photometric night for which images of M15 were taken. Computing the mean values of these bins we were able to construct the histogram shown in Fig. 1. We scaled this histogram to a 200-s exposure-time image to account for the mean exposure time of our science images. We obtained a mean completeness value of $i_{\text{complete}} = 18.4 \pm 0.3$ mag and

Fig. 2. An example of the sensitivity function for our AstraLux observations. We show the results for KOI-0717 for an image with the 10% selection rate. Color code represents the measured S/N for the detection of the artificial companion profile. The white lines represent the contours for the 3- σ (lower line) and 10- σ (upper line) S/N detections.

found that our faintest detected source has $i = 22.5$ mag. In the case of the SDSSz observations, we adapted the exposure time to detect the companion seen in the SDSSi image. It is important to remember that these values were calculated for a particular exposure time. Since we set different exposure times for each target in order to achieve $\Delta m_i \approx 5.0$ (see lower panel in Fig. 3), the completeness and detectability limits should be different for each image. For each particular science image, the scaled values of i_{complete} related to its real exposure time are shown in Table 4. We note that we only show here the observations for the non-isolated KOIs (*Kepler* host candidates without any objects closer than 6 arcsec).

Sensitivity functions were compiled for each image to determine the depth in angular separation and magnitude (actually, Δm) to which we are complete for a 3- σ detection threshold.

By measuring the observed radial profile averaged over a large number of directions (avoiding angles in the direction of close companions), we were able to infer the dependence of the primary star brightness along the angular separation. We then, iteratively added the similar profiles but located at different angular separations in the range 0.2–3.0 arcsec and scaled them to be Δm magnitudes fainter according to the expression $F_{/C} = F_p 10^{-0.4\Delta m}$, where $F_{/C}$ is the encircled flux of the companion and F_p the flux of the primary. We then measured the S/N of the detection of the added profile. Figure 2 shows an example of these calculations where the artificial companion to the observed KOI profile have differential magnitudes of $\Delta m = [0, 7]$ and angular separations 0.2–3 arcsec.

3. Results

We found 111 companion sources at angular separations of 0.3–10 arcsec from the 98 targeted KOIs. Since the *Kepler* PSF varies from 6 to 10 arcsec, we consider a KOI to be isolated if no objects smaller than 6 arcsec are found in our lucky imaging observations. Objects with larger angular separations could be easily detected by the *Kepler* images or previous ground-based all-sky surveys.

According to this definition, we detected 57 isolated KOIs. This means a 58.2% rate of isolated objects for planet-host

Fig. 3. *Upper panel:* cumulative observed-companion fraction (ocf , see text) for the double (green), triple (purple), and quadruple (orange) systems as well as the total ocf (black). We also show the values for the double system at 3 and 6 arcsec. *Middle and lower panels:* calibrated SDSS*i* magnitude of the 111 companions and differential magnitude with their KOIs. Dashed lines mark the 3 and 6 arcsec positions.

candidates in the *Kepler* objects of interest catalog. It is important to remark that this isolation rate would decrease to 33.7% if we considered a 10 arcsec PSF for *Kepler* observations. However, the most accurate PSF of 6 arcsec is considered in this paper.

Among the KOIs with visible companions at angular separations of 6 arcsec, 41 planet-host candidates have, at least, one object within this projected separation (i.e., 41.8%). Among these, 17 KOIs have a total amount of 19 companions within 3 arcsec (17.3% of all KOIs considered). We refer to this group in this paper as the close companions' group. In Fig. 5, we show the 17 KOIs with close companions and the *Kepler* optimal (public) apertures of the different quarters into which the *Kepler* mission is divided. All 19 companions lie within these apertures contaminating the light curve fluxes as well as the corresponding planet-star properties and planet validation. Moreover, 27 KOIs have 30 companions within the range 3–6 arcsec (27.6% of all KOIs considered), medium-distance group. This means that 3 of the main targets from the close companion group (KOI-0433, KOI-0641, and KOI-0841, see Fig. 4) have either close (<3 arcsec) or medium-separation (3–6 arcsec) sources. Figure 6 and Table 2 summarize these results. In a forthcoming paper, we will present a comparison with the speckle and AO results by Howell et al. (2011) and Adams et al. (2012).

According to all these numbers, we defined the observed companion fraction as $ocf = \frac{n}{s+n}$, where n is the number of objects within a certain angular separation from the KOI of each particular type of system (either double, triple, or quadruple) and s is the number of isolated KOIs found in our sample (i.e., $s = 57$). The cumulative ocf is plotted in the upper panel of Fig. 3. We show there that for a given KOI, the probability of having a double (visual) system within 3 arcsec is 21%, while if we go further away until 6 arcsec, this probability increases to 37%. The same was done for triple systems (purple in upper panel of Fig. 3) for which we found that only 3% of the KOIs have more than 1 visual companion within 3 arcsec. No quadruple systems were detected in our sample within 6 arcsec (orange line in the mentioned figure). We also plot a total observed-companion fraction (black line) taking into account the contributions from all type of systems. This was defined as $ocf(\text{Total}) = \frac{d+t+q}{s+d+t+q}$, where d , t , and q are the double, triple, and quadruple systems found within a certain angular separation, a similar definition as the one presented by Duchêne (1999). We note that in the upper panel of Fig. 3 only the ocf_{Total} monotonically increases as we move away from the primary. The decreasing cumulative ocf at 7–8 arcsec for the double systems is due to our reaching the position of the third component of a triple system, which is automatically accounted for the triple sample and removed from the double sample. There is a similar explanation for the decreasing cumulative ocf of the triple system.

In Table 5, we present our photometric measurements in the SDSS*i* and SDSS*z* bands for KOIs with detected close (<3 arcsec) companions. In this table, we also provide the angular separations between the stellar companions and the assumed KOI, as well as the angular position from north towards east. We note that in cases where both objects have similar magnitudes it is impossible with our observations to infer which of the two is actually the one that harbors the transit (high-resolution imaging in- and out-of-transit should be performed to this end). To avoid errors coming from the calibration process, we measured the differential magnitudes Δi and Δz directly from the instrumental magnitudes. The $i - z$ color was derived directly from the calibrated magnitudes for the primary (brighter) star. To minimize the large errors due to the faintness of the majority of the close companions, we obtained the $(i - z)_C$ color of the companion by using the expression

$$(i - z)_C = \Delta i - \Delta z + (i - z)_P, \quad (5)$$

where $(i - z)_P$ represents the color of the primary star.

Owing to our limited observing time, we only obtained SDSS*z* images for KOIs found to have very close companions (<3 arcsec) in an on-the-fly reduction. Hence, we lack $i - z$ colors for companions at angular separations of 3–6 arcsec. Photometric and astrometric information available from our observations for these medium-separation sources is shown in Table 6. We note that KOIs with both companions within 3–6 arcsec and at least one object within 0.3–3 arcsec, do have SDSS*z* photometry.

Reconnaissance spectra were acquired for 25 KOIs in order to more accurately derive their spectral types and physical parameters such as temperature and surface gravity. Moreover, as explained in Borucki et al. (2011) this kind of observations is able to reject the possibility of a very close (<0.2 arcsec) binary that would produce a grazing eclipse, since this type of binary would have a radial velocity of tens of km/s. The data is now being analyzed and will be published in a future paper (Lillo-Box et al., in prep.).

Fig. 4. High-resolution images of the three KOIs with companions in both the 0–3 arcsec and 3–6 arcsec ranges. The images are 12×12 arcsec and the KOI is placed at the center of the image. Companions are sorted by angular separation in Table 6. North is up and east is left.

4. Discussion

4.1. Spectral types of the stellar components

We applied two different methods to determine the spectral type (effective temperature) of the stellar companions according to their angular separation.

4.1.1. Spectral energy distributions for 3–6 arcsec companions

Among the 27 KOIs with stellar companions at 3–6 arcsec, we found 2MASS counterparts (Cutri et al. 2003) for around one third of the detected companions (11 out of 30). We assumed an error of 1.5 arcsec for the cross-match between the catalogs. A visual inspection of the 2MASS images was carried out to ensure the accuracy of the match. Together with our SDSSi magnitudes, we performed a spectral energy distribution (SED) fitting with the Virtual Observatory SED Analyzer tool (VOSA, Bayo et al. 2008, and in prep.) to determine the effective temperature of our objects. The new version of this tool allows us to fit the extinction along the line of sight. The results show values for the A_v parameter in the range $A_v = 0$ –1.0. Here we assumed a solar metallicity and two surface gravities to account for two possible types of companion at different evolutionary stages: main-sequence foreground or bounded stars ($\log(g) = 4.5$) or background giant stars ($\log(g) = 3.5$). Table 7 summarizes the fit results, according to which these companions are mostly K-type stars if we assume a main-sequence stage. We note that all KOIs are hotter (earlier spectral types) than the possible companions. We found an rms ~ 200 K between our fitting results and the KIC effective temperatures. Constraints on the distances for these objects are explained in Sect. 4.2.1.

4.1.2. Spectral types for close companions

Assuming a main-sequence nature for the secondary, we were able to estimate their spectral types by using the $i - z$ color. Synthetic spectra from Pickles (1998) for main-sequence stars

were convolved with the SDSSi and SDSSz transmission curves⁵ following the same scheme as in Daemgen et al. (2009) to derive a relation between the spectral type and the aforementioned $i - z$ color. We overplotted our $i - z$ colors in this diagram to estimate the companion spectral types. The typical errors depend on the spectral type since they are determined according to the photometric error in the calculation of the $i - z$ values. In particular, we note that, since the dependence of the spectral type on the aforementioned color is stronger for types later than K5–K6, errors will be much smaller than for earlier types, for which the dependence is weaker. Thus, only stellar companions with $i - z > 0.21$ (corresponding to a K5–K6 main-sequence star) are considered in this analysis. In Fig. 7, we show the results for the nine companions and two primaries with estimated spectral types later than K5 (see Table 3).

As expected, these objects are cool, low-mass stars (late K or early M). Their physical association are discussed in Sect. 4.2.

4.2. On the physical association of the visual companions

Although the physical bound of the blended stars do not affect our previous calculations, it is important to determine whether the visual companions are, indeed, bounded. Several multiple-star systems have been discovered, both circumbinary planets, for instance Kepler-16b (Doyle et al. 2011), and binary systems with the planet orbiting one of the components of the couple as HD196885Ab (see Thebault 2011). These objects represent a challenge for theoretical models of planet formation, for instance, in terms of orbital stability (see Holman & Wiegert 1999). Moreover, it has been discovered that around one fifth of known exoplanets inhabit double or multiple stellar systems (Desidera & Barbieri 2007; Mugrauer & Neuhäuser 2009; Thebault 2011).

4.2.1. Medium-distance companions

We can infer approximate distances to the KOIs and companions analyzed in the previous section by performing a SED fitting

⁵ See

<http://www.sdss.org/dr3/instruments/imager/index.html>

Fig. 5. High-resolution SDSS images of the close companions detected around 3 arcsec of the 17 *Kepler* objects of interest. North towards up and east towards left. Different sizes are used for each image to clearly show all features. Black arrows indicate the position of the faintest targets and the horizontal black line represents 2 arcsec on each image. Green polygons represent the optimal public *Kepler* apertures used on each quarter of the *Kepler* mission to compute the light curves. The brighter object assumed to be the KOI is centered on the images for reconnaissance purposes.

Fig. 6. Main multiplicity results of our survey. Isolated KOIs are represented by the green circle. *Kepler* objects of interest with objects within 3–6 arcsec are represented by the blue color. The close-companion group (KOIs with at least one source within 0.3–3.0 arcsec) is shown in red. Note that 3 KOIs (KOI-0433, KOI-0641, and KOI-0841) have objects either in the close- and medium-distance groups.

Table 2. Cumulative percentage of KOIs with visual (even bounded or not) and bound companions according to our observations.

	Within 3''	Within 6''	Within 10''
Visual	17.3%	41.8%	66.3%
Bounded	6.1–9.2%	6.1–9.2%	–

Notes. *Visual* means here any kind of stellar source detected around the KOI, regardless of whether they are bounded. The *bounded* sample refers to those objects probably bounded according to the study performed in Sect. 4.2.

using the total flux emitted by the star (F_{tot}) according to the effective temperature estimated by VOSA. From this temperature and assuming a luminosity class, we were able to estimate the bolometric magnitude of the star using the relations in Schmidt-Kaler (1982). Hence, we were able to derive a luminosity L_* and hence the distance since $L_* = 4\pi d^2 F_{\text{tot}}$. For the KOIs, we assumed a main-sequence stage but two distances were calculated for the stellar companions assuming both main-sequence and giant stages. The errors were calculated by taking into account the uncertainties in F_{tot} and assuming an error of 125 K in the temperature calculation for the L_* derivation. The former uncertainty also includes the errors in the effective temperature and metallicity fitted by VOSA. The results are shown in the last column of Table 7.

The giant scenario for the companion does not seem to work for most companions since it leads to very large distances ($d > 21$ Kpc, the Galaxy limit along the *Kepler* line-of-sight). Thus, the main-sequence scenario is the only possibility for them. According to it, one (KOI-0623C) in ten of the companions that could be fitted by VOSA has a distance in good agreement with its corresponding KOI. Among the remaining eight possible companions, seven are found to be background main-sequence stars and one (KOI-212C) is a probable foreground M-dwarf of spectral type M4V.

4.2.2. Close companions

Morton & Johnson (2011, hereafter MJ11) estimated the probability of a given target in the *Kepler* field having a background source brighter than $m_k = 24.0$ within 2 arcsec, finding that

Table 3. Estimated spectral types for objects with $i - z > 0.21$.

Object	Lower Limit SpT	SpT	Upper Limit SpT
KOI-0641A	K5	K7	K9
KOI-0641B	M1	M3	M3
KOI-0641C	M3	M5	M5
KOI-0703B	K9	M1	M3
KOI-0298A	K5	K7	K9
KOI-0298B	K9	M0	M2
KOI-0658B	M3	M3	M3
KOI-0401B	K9	K9	M1
KOI-0422B	M5	M5	M6
KOI-0645B	K9	K9	M1
KOI-0433B	M3	M5	M6

Notes. Second and third columns represent the lower and upper limits (respectively) for the spectral type determination according to the method described in the text. Since no decimals have been considered, we estimate an error of one subclass for those with no differences between the error limits and the central value.

Fig. 7. Spectral type estimation for the stellar companions with $i - z > 0.21$ corresponding to spectral types later than K5–K6. Red asterisks represent the synthetic values calculated by convolving the spectral library from Pickles (1998) with the transmission curves of the Sloan filters. Blue open circles represent the position of standard stars from Smith et al. (2002). Green filled squares are the measurements for our detected companions and their error bars (assuming no error in the software gain).

this value strongly depends on the *Kepler* magnitude (m_k) and Galactic latitude (b) of the target. Since 90% of our primary targets have *Kepler* magnitudes in the range 13.0–15.5 and taking into account Eq. (8) in MJ11, we derive a background-source probability-range of 4–40% depending on the particular values of b and m_k for each target. However, as we have previously said, we reach a completeness of $i = 18.5$, which translates into $m_k = 18.8$ according to a simple transformation with $r^2 = 0.97$ using both KIC magnitudes. Hence, we underestimate the chance-aligned probability with respect to the one in MJ11. We found 11 blended sources at less than 2 arcsec in 10 parent stars. This means 10.2% of our sample, which, since it is a lower limit, clearly agrees with the values of MJ11.

Even though our photometric measurements do not provide enough information to clearly establish whether there is a gravitational bound (if any) in the system, we were able to infer some evidence by analyzing several aspects of the available magnitudes of the A and B/C components. We constructed an empirical zero-age main-sequence (ZAMS) based on the synthetic

Table 4. Observing information of the 41 non-isolated objects in our sample.

KOI ID	RA ^a J2000.0	Dec ^a J2000.0	Date	Exptime ^b s	Filter	<i>i</i> _{Complete} mag	<i>i</i> _{Detect} ^c mag
99	19:41:44.23	+44:31:52.0	05jul.11	60.0	<i>i</i>	16.34	19.94
131	19:56:23.42	+43:29:51.4	10jul.11	150.0	<i>i</i>	17.34	20.94
212	19:44:33.54	+41:36:11.5	09jul.11	240.0	<i>i</i>	17.65	21.25
232	19:24:26.86	+39:56:56.8	02jul.11	200.0	<i>i</i>	18.40	22.00
238	19:47:59.68	+42:46:55.2	05jul.11	200.0	<i>i</i>	17.65	21.25
298	19:21:58.61	+52:03:19.8	12jun.11	160.0	<i>i</i>	17.41	21.01
298	19:21:58.61	+52:03:19.8	12jun.11	200.0	<i>z</i>	—	—
326	19:06:37.44	+46:47:00.6	12jun.11	200.0	<i>i</i>	18.40	22.00
343	19:40:28.52	+48:28:52.7	12jun.11	200.0	<i>i</i>	18.40	22.00
372	19:56:29.40	+41:52:00.5	01jul.11	34.0	<i>i</i>	16.48	20.08
372	19:56:29.40	+41:52:00.5	01jul.11	40.0	<i>z</i>	—	—
375	19:24:48.28	+51:08:39.5	02jul.11	87.0	<i>i</i>	17.50	21.10
379	19:28:13.62	+37:46:34.3	25jul.11	140.0	<i>i</i>	17.65	21.25
379	19:28:13.62	+37:46:34.3	25jul.11	140.0	<i>z</i>	—	—
387	19:08:52.48	+38:51:45.0	02jul.11	90.0	<i>i</i>	17.53	21.13
387	19:08:52.48	+38:51:45.0	02jul.11	100.0	<i>z</i>	—	—
401	19:03:24.88	+38:23:02.8	05jul.11	200.0	<i>i</i>	18.40	22.00
401	19:03:24.88	+38:23:02.8	05jul.11	200.0	<i>z</i>	—	—
433	19:54:12.20	+48:19:57.0	07jul.11	200.0	<i>i</i>	17.65	21.25
433	19:54:12.20	+48:19:57.0	07jul.11	200.0	<i>z</i>	—	—
439	19:45:37.66	+51:21:29.5	11jun.11	200.0	<i>i</i>	18.40	22.00
465	19:35:42.83	+45:08:33.0	10jul.11	200.0	<i>i</i>	17.65	21.25
520	19:38:40.31	+43:51:11.9	08jul.11	200.0	<i>i</i>	18.40	22.00
548	19:18:00.18	+51:41:08.5	09jun.11	200.0	<i>i</i>	18.40	22.00
555	19:32:29.62	+40:56:05.3	10jun.11	200.0	<i>i</i>	18.40	22.00
592	19:37:51.02	+46:49:17.4	07jul.11	200.0	<i>i</i>	17.65	21.25
592	19:37:51.02	+46:49:17.4	08jul.11	200.0	<i>z</i>	—	—
611	19:53:10.57	+41:41:01.7	02jul.11	200.0	<i>i</i>	18.40	22.00
623	19:40:54.34	+50:33:32.4	05jul.11	30.0	<i>i</i>	16.34	19.94
626	19:40:46.42	+39:32:22.9	04jul.11	180.0	<i>i</i>	18.09	21.69
626	19:40:46.42	+39:32:22.9	04jul.11	180.0	<i>z</i>	—	—
628	19:14:47.69	+39:42:29.9	04jul.11	200.0	<i>i</i>	18.40	22.00
628	19:14:47.69	+39:42:29.9	04jul.11	160.0	<i>z</i>	—	—
638	19:42:14.26	+40:14:10.7	05jul.11	140.0	<i>i</i>	17.65	21.25
641	19:57:11.88	+40:14:06.4	01jul.11	87.0	<i>i</i>	17.50	21.10
641	19:57:11.88	+40:14:06.4	01jul.11	87.0	<i>z</i>	—	—
644	19:19:52.03	+40:31:57.7	04jul.11	180.0	<i>i</i>	18.09	21.69
644	19:19:52.03	+40:31:57.7	04jul.11	180.0	<i>z</i>	—	—
645	19:40:52.18	+40:35:32.3	26jun.11	200.0	<i>i</i>	17.65	21.25
645	19:40:52.18	+40:35:32.3	26jun.11	200.0	<i>z</i>	—	—
658	19:48:21.60	+41:23:16.8	01jul.11	200.0	<i>i</i>	18.40	22.00
658	19:48:21.60	+41:23:16.8	01jul.11	200.0	<i>z</i>	—	—
685	19:41:54.17	+43:29:35.2	11jun.11	200.0	<i>z</i>	—	—
685	19:41:54.17	+43:29:35.2	11jun.11	200.0	<i>i</i>	18.40	22.00
703	19:39:38.88	+45:34:00.1	11jun.11	60.0	<i>i</i>	16.89	20.49
703	19:39:38.88	+45:34:00.1	11jun.11	200.0	<i>z</i>	—	—
704	18:57:32.69	+45:43:10.9	05jul.11	150.0	<i>i</i>	17.65	21.25
721	19:48:16.42	+46:50:03.5	26jun.11	140.0	<i>i</i>	17.65	21.25
721	19:48:16.42	+46:50:03.5	26jun.11	140.0	<i>z</i>	—	—
841	19:28:56.82	+41:05:09.2	11jun.11	200.0	<i>i</i>	18.40	22.00
841	19:28:56.82	+41:05:09.2	11jun.11	200.0	<i>z</i>	—	—
881	19:39:38.34	+42:56:07.1	11jun.11	200.0	<i>i</i>	18.40	22.00
1032	19:27:54.61	+37:31:57.4	06jul.11	150.0	<i>i</i>	18.09	21.69
1192	19:24:07.70	+38:42:14.0	06jul.11	200.0	<i>i</i>	17.65	21.25
1375	19:13:16.90	+42:15:41.0	06jul.11	150.0	<i>i</i>	17.34	20.94
1375	19:13:16.90	+42:15:41.0	06jul.11	150.0	<i>z</i>	—	—
1527	19:46:41.12	+43:29:54.2	07jul.11	200.0	<i>i</i>	17.41	21.01
1573	19:47:23.06	+40:08:19.0	08jul.11	200.0	<i>i</i>	18.40	22.00
1574	19:51:40.07	+46:57:54.4	06jul.11	200.0	<i>i</i>	17.65	21.25

Notes. ^(a) Right ascension and Declination from [Borucki et al. \(2011\)](#). ^(b) Effective exposure time of the image. As the selection rate was of 10% for all the images, one must multiply this column by 10 to obtain the real exposure time. ^(c) Estimated completeness and detectability magnitudes scaled to the ones found for the globular cluster M15 (see Sect. 2.3.6) by the exposure time of each particular image.

Table 5. Photometric and astrometric results for companions closer than 3 arcsec detected in our KOI sample (19 companions to 17 KOIs).

KOI	Comp.	Angular sep. arcsec	Angle (deg) degrees	Phot?	SDSSi mag	SDSSz mag	Δi mag	Δz mag	$(i - z)$ mag	$(i - z)_{\text{unc}}$ mag
298	A*	0.000	0.0	P	13.16 ± 0.15	12.88 ± 0.16	0.0 ± 0.12	0.0 ± 0.16	0.273 ± 0.073	0.22
	B+	1.963	273.09	P	13.64 ± 0.18	13.23 ± 0.20	0.48 ± 0.16	0.35 ± 0.2	0.405 ± 0.073	0.34
	C	1.961	93.56	P	17.59 ± 0.53	–	4.43 ± 0.53	–	–	–
379	A*	0.000	0.0	N	13.29 ± 0.07	13.22 ± 0.08	0.0 ± 0.05	0.0 ± 0.06	0.07 ± 0.047	0.11
	B+	1.898	80.44	N	14.25 ± 0.09	14.10 ± 0.09	0.96 ± 0.07	0.88 ± 0.08	0.15 ± 0.048	0.15
387	A	0.000	0.0	N	12.80 ± 0.25	12.79 ± 0.22	0.0 ± 0.35	0.0 ± 0.28	0.0080 ± 0.101	0.33
	B	0.894	350.78	N	16.05 ± 0.96	16.05 ± 0.75	3.25 ± 0.99	3.26 ± 0.77	–0.0040 ± 0.102	1.3
401	A	0.000	0.0	Y	13.76 ± 0.07	13.69 ± 0.07	0.0 ± 0.04	0.0 ± 0.06	0.07 ± 0.049	0.1
	B+	1.946	269.98	Y	16.35 ± 0.21	15.97 ± 0.22	2.59 ± 0.2	2.27 ± 0.22	0.383 ± 0.049	0.32
433	A	0.000	0.0	Y	14.67 ± 0.19	14.54 ± 0.19	0.0 ± 0.18	0.0 ± 0.18	0.13 ± 0.27	0.27
	B+	2.326	5.64	Y	18.13 ± 0.19	17.52 ± 0.19	4.0 ± 0.18	2.98 ± 0.18	0.89 ± 0.29	0.27
592	A	0.000	0.0	Y	14.13 ± 0.07	14.57 ± 0.06	0.0 ± 0.0	0.0 ± 0.0	–0.444 ± 0.076	0.09
	B	2.264	151.3	Y	17.94 ± 0.36	18.02 ± 0.39	3.81 ± 0.35	3.46 ± 0.38	–0.094 ± 0.522	–
626	A	0.000	0.0	N	13.36 ± 0.07	13.37 ± 0.09	0.0 ± 0.0	0.0 ± 0.0	–0.01 ± 0.081	0.11
	B	2.694	349.02	N	18.30 ± 0.36	18.34 ± 0.41	4.95 ± 0.36	4.97 ± 0.4	–0.036 ± 0.086	0.55
628	A	0.000	0.0	N	13.69 ± 0.07	13.75 ± 0.09	0.0 ± 0.0	0.0 ± 0.0	–0.061 ± 0.081	0.11
	B	1.765	311.42	N	17.43 ± 0.33	17.41 ± 0.37	3.75 ± 0.32	3.67 ± 0.36	0.018 ± 0.082	0.5
	C	2.695	239.68	N	17.84 ± 0.33	17.79 ± 0.37	4.16 ± 0.32	4.05 ± 0.36	0.13 ± 0.084	0.69
641	A*	0.000	0.0	P	13.25 ± 0.12	12.99 ± 0.13	0.0 ± 0.02	0.0 ± 0.08	0.265 ± 0.087	0.17
	B+	2.206	277.22	P	14.90 ± 0.12	14.36 ± 0.19	1.65 ± 0.03	1.37 ± 0.16	0.54 ± 0.087	0.23
644	A	0.000	0.0	N	13.43 ± 0.07	13.31 ± 0.09	0.0 ± 0.0	0.0 ± 0.0	0.123 ± 0.081	0.11
	B	2.636	63.63	N	14.87 ± 0.08	14.73 ± 0.09	1.44 ± 0.04	1.43 ± 0.04	0.136 ± 0.081	0.12
645	A	0.000	0.0	Y	13.55 ± 0.06	13.51 ± 0.06	0.0 ± 0.0	0.0 ± 0.0	0.043 ± 0.038	0.08
	B+	2.78	50.83	Y	15.72 ± 0.08	15.33 ± 0.09	2.17 ± 0.05	1.82 ± 0.06	0.387 ± 0.038	0.11
658	A	0.000	0.0	P	13.74 ± 0.06	13.72 ± 0.06	0.0 ± 0.0	0.0 ± 0.0	0.018 ± 0.064	0.08
	B+	1.865	240.08	P	18.38 ± 0.29	17.79 ± 0.30	4.63 ± 0.29	4.06 ± 0.3	0.588 ± 0.067	0.42
703	A	0.000	0.0	P	13.01 ± 0.11	13.06 ± 0.12	0.0 ± 0.0	0.0 ± 0.0	–0.052 ± 0.087	0.16
	B+	1.89	34.44	P	19.50 ± 0.41	19.04 ± 0.6	6.48 ± 0.4	5.98 ± 0.59	0.452 ± 0.112	0.73
704	A	0.000	0.0	Y	13.45 ± 0.06	–	0.0 ± 0.0	–	–	–
	B	1.657	180.36	Y	18.47 ± 0.61	–	5.02 ± 0.6	–	–	–
721	A	0.000	0.0	Y	13.52 ± 0.06	13.44 ± 0.06	0.0 ± 0.01	0.0 ± 0.03	0.075 ± 0.038	0.08
	B	1.844	195.67	Y	17.37 ± 0.13	17.28 ± 0.14	3.85 ± 0.12	3.84 ± 0.13	0.092 ± 0.04	0.2
841	A	0.000	0.0	P	15.57 ± 0.26	15.52 ± 0.26	0.0 ± 0.18	0.0 ± 0.18	0.05 ± 0.37	0.37
	B	1.956	69.13	P	19.25 ± 0.26	19.16 ± 0.26	3.68 ± 0.18	3.64 ± 0.19	–0.01 ± 0.42	0.37
1375	A	0.000	0.0	Y	13.24 ± 0.23	13.29 ± 0.19	0.0 ± 0.32	0.0 ± 0.25	–0.051 ± 0.057	0.3
	B	0.796	266.46	Y	15.99 ± 0.55	16.23 ± 0.46	2.75 ± 0.59	2.94 ± 0.49	–0.241 ± 0.059	0.82

Notes. Objects marked with an asterisk (*) in the *companion* column are assumed to be the *Kepler* object of interest. In the case of close companions with similar magnitudes, it is difficult to distinguish which is the actual host. The assumed KOI is the brightest object in the system. Companions marked with a “+” symbol indicate those probably bound according to Sect. 4.2.2. The last column shows the photometric error if we were to take into account the empirical errors in the software gain of the instrument.

Table 6. Photometric and astrometric results for companions between 3–6 arcsec detected in our KOI sample (30 companions to 27 KOIs).

KOI	Comp.	Angular Sep. arcsec	Angle (deg) degrees	Phot?	SDSSi mag	SDSSz mag	Δi mag	Δz mag	$(i - z)$ mag
99	A	0.000	0.0	Y	12.57 ± 0.18	–	0.00 ± 0.18	–	–
99	B	3.383	49.3	Y	17.96 ± 0.18	–	5.39 ± 0.19	–	–
99	C	5.997	338.3	Y	16.58 ± 0.18	–	4.01 ± 0.18	–	–
131	A	0.000	0.0	Y	13.53 ± 0.17	–	0.00 ± 0.18	–	–
131	B	5.540	154.6	Y	17.00 ± 0.17	–	3.48 ± 0.18	–	–
212	A	0.000	0.0	P	14.70 ± 0.19	–	0.00 ± 0.18	–	–
212	B	4.812	308.8	P	17.52 ± 0.19	–	2.82 ± 0.18	–	–
232	A	0.000	0.0	N	13.76 ± 0.16	–	0.00 ± 0.18	–	–
232	B	5.550	22.3	N	18.19 ± 0.16	–	4.43 ± 0.18	–	–
238	A	0.000	0.0	Y	13.74 ± 0.18	–	0.00 ± 0.18	–	–
238	B	3.769	328.7	Y	20.61 ± 0.24	–	6.87 ± 0.24	–	–
326	A	0.000	0.0	P	14.84 ± 0.26	–	0.00 ± 0.18	–	–
326	B	3.452	269.4	P	16.61 ± 0.26	–	1.77 ± 0.18	–	–
343	A	0.000	0.0	P	13.06 ± 0.26	–	0.00 ± 0.18	–	–
343	B	4.938	145.8	P	–	–	–	–	–
372	A	0.000	0.0	P	12.25 ± 0.18	12.12 ± 0.18	0.00 ± 0.18	0.00 ± 0.18	0.13 ± 0.25
372	B	5.962	36.1	P	16.88 ± 0.18	16.58 ± 0.18	4.64 ± 0.18	4.45 ± 0.18	0.30 ± 0.25
375	A	0.000	0.0	N	13.08 ± 0.15	–	0.00 ± 0.18	–	–
375	B	5.329	156.1	N	18.06 ± 0.16	–	4.98 ± 0.18	–	–
433	A	0.000	0.0	Y	14.67 ± 0.19	14.54 ± 0.19	0.00 ± 0.18	0.00 ± 0.18	0.13 ± 0.27
433	C	3.670	293.4	Y	17.26 ± 0.19	17.07 ± 0.19	2.60 ± 0.18	2.53 ± 0.18	0.19 ± 0.27
439	A	0.000	0.0	P	14.11 ± 0.32	–	0.00 ± 0.18	–	–
439	B	5.453	16.9	P	19.45 ± 0.32	–	5.34 ± 0.19	–	–
465	A	0.000	0.0	Y	13.94 ± 0.17	–	0.00 ± 0.18	–	–
465	B	3.580	130.8	Y	18.30 ± 0.17	–	4.35 ± 0.18	–	–
465	C	4.527	193.1	Y	17.82 ± 0.17	–	3.87 ± 0.18	–	–
520	A	0.000	0.0	N	14.30 ± 0.17	–	0.00 ± 0.18	–	–
520	B	5.628	271.7	N	18.14 ± 0.17	–	3.84 ± 0.18	–	–
548	A	0.000	0.0	N	13.37 ± 0.50	–	0.00 ± 0.18	–	–
548	B	4.597	133.9	N	18.33 ± 0.50	–	4.96 ± 0.18	–	–
555	A	0.000	0.0	N	14.29 ± 0.18	–	0.00 ± 0.18	–	–
555	B	4.021	23.1	N	17.86 ± 0.18	–	3.58 ± 0.18	–	–
611	A	0.000	0.0	N	13.75 ± 0.15	–	0.00 ± 0.18	–	–
611	B	5.999	324.2	N	19.18 ± 0.16	–	5.44 ± 0.18	–	–
623	A	0.000	0.0	Y	11.55 ± 0.18	–	0.00 ± 0.18	–	–
623	B	5.540	202.0	Y	14.07 ± 0.18	–	2.52 ± 0.18	–	–
638	A	0.000	0.0	Y	13.51 ± 0.17	–	0.00 ± 0.18	–	–
638	B	5.938	65.5	Y	19.43 ± 0.19	–	5.92 ± 0.19	–	–
641	A	0.000	0.0	P	13.25 ± 0.12	12.99 ± 0.13	0.00 ± 0.02	0.00 ± 0.08	0.27 ± 0.17
641	C	3.653	206.1	P	13.38 ± 0.16	12.89 ± 0.17	0.29 ± 0.18	0.08 ± 0.18	0.49 ± 0.23
685	A	0.000	0.0	P	13.71 ± 0.3	–	0.00 ± 0.18	–	–
685	B	3.268	271.1	P	19.24 ± 0.3	–	5.54 ± 0.18	–	–
841	A	0.000	0.0	P	15.57 ± 0.26	15.52 ± 0.26	0.00 ± 0.18	0.00 ± 0.18	0.05 ± 0.37
841	C	5.599	41.5	P	17.19 ± 0.26	17.20 ± 0.26	1.62 ± 0.18	1.68 ± 0.18	-0.01 ± 0.37
881	A	0.000	0.0	P	15.58 ± 0.26	–	0.00 ± 0.18	–	–
881	B	5.264	191.5	P	20.70 ± 0.29	–	5.12 ± 0.22	–	–
1032	A	0.000	0.0	Y	13.47 ± 0.17	–	0.00 ± 0.18	–	–
1032	B	5.856	320.3	Y	18.90 ± 0.17	–	5.43 ± 0.18	–	–
1032	C	5.883	86.1	Y	18.42 ± 0.17	–	4.94 ± 0.18	–	–
1192	A	5.643	195.1	Y	12.52 ± 0.17	–	0.00 ± 0.18	–	–
1192	B	0.000	0.0	Y	17.82 ± 0.17	–	5.30 ± 0.18	–	–
1527	A	0.000	0.0	Y	14.73 ± 0.19	–	0.00 ± 0.18	–	–
1527	B	5.908	346.9	Y	17.40 ± 0.19	–	2.67 ± 0.18	–	–
1573	A	0.000	0.0	N	14.17 ± 0.17	–	0.00 ± 0.18	–	–
1573	B	3.933	300.1	N	18.84 ± 0.17	–	4.68 ± 0.18	–	–
1574	A	0.000	0.0	Y	14.26 ± 0.16	–	0.00 ± 0.18	–	–
1574	B	5.035	224.6	Y	18.92 ± 0.17	–	4.66 ± 0.18	–	–

Notes. Only objects with additional companions within 3 arcsec have magnitudes in the SDSSz. KOI-0372 also has this information because during the observing run it had seemed to have a close companion that, however, after the reduction was discarded.

griz photometry derived by Ofek (2008) for Tycho-2 stars with HIPPARCOS B_T and V_T bands, as well as 2MASS JHK magnitudes (see Fig. 8). To reach the substellar domain, we added

the Moraux et al. (2003) *iz* photometry for 109 brown dwarfs in the Pleiades region assuming a distance to the cluster of 130 pc (Stello & Nissen 2001). As we are interested in possible binary

Table 7. Spectral-energy-distribution fitting results for the medium-distance companions with 2MASS counterparts.

KOI	Comp.	RA ^a	Dec ^a	T_{eff}	$\log(g)$	χ^2	SpT	Model ^b	D (pc)
131	A	299.097600	43.497601	6500.0	4.5	0.47	F5	Kurucz	1120 ⁺¹⁰⁰ ₋₁₂₀
	B	299.098259	43.496210	5500.0	4.5	0.90	G8	Kurucz	2510 ⁺³³⁰ ₋₃₅₀
	B	299.098259	43.496210	5400.0	3.5	0.86	G3	NextGen	— ^d
212	A	296.139750	41.603199	5800.0	4.5	0.92	G4	NextGen	1010 ⁺²³⁰ ₋₁₃₀
	B	296.138708	41.604036	4400.0	4.5	5.66	K5	NextGen	1760 ⁺²³⁰ ₋₂₄₀
	C	296.139026	41.601652	3400.0	4.5	0.61	M4	COND00	366 ⁺¹³⁶ ₋₉₄
	B	296.138708	41.604036	4200.0	3.5	5.55	K3	NextGen	— ^d
	C	296.139026	41.601652	3100.0	3.5	2.34	>M6	COND00	— ^c
372	A	299.122500	41.866798	5750.0	4.5	1.21	G5	Kurucz	314 ⁺⁸⁵ ₋₃₈
	B	299.123475	41.868137	4600.0	4.5	0.68	K4	NextGen	1340 ⁺²³⁰ ₋₁₈₀
	B	299.123475	41.868137	4400.0	3.5	0.67	K2	NextGen	— ^d
375	A	291.201150	51.144299	5800.0	4.5	1.60	G4	NextGen	495 ⁺¹¹² ₋₆₅
	B	291.201750	51.142945	3500.0	4.5	1.41	M3	NextGen	831 ⁺¹²³ ₋₂₁₂
	B	291.201750	51.142945	3100.0	3.5	3.04	>M6	COND00	— ^c
520	A	294.667950	43.853298	5200.0	4.5	5.36	K0	NextGen	567 ⁺⁶⁶ ₋₆₀
	B	294.666387	43.853345	3600.0	4.5	14.80	M2	DUSTY00	1020 ⁺¹⁷⁰ ₋₁₃₀
	B	294.666387	43.853345	3900.0	3.5	15.70	K6	COND00	— ^d
623	A	295.226400	50.558998	6250.0	4.5	1.16	F7	Kurucz	411 ⁺⁵⁹ ₋₆₀
	B	295.225822	50.557572	4800.0	4.5	2.41	K3	NextGen	439 ⁺⁴⁷ ₋₅₅
	B	295.225822	50.557572	4400.0	3.5	1.88	K2	NextGen	7920 ⁺⁹⁶⁰ ₋₁₃₀₀
641	A	299.299500	40.235100	3600.0	4.5	1.29	M2	DUSTY00	117 ⁺¹⁹ ₋₁₅
	C	299.299054	40.234189	3400.0	4.5	1.60	M4	NextGen	76 ⁺²⁸ ₋₂₀
	C	299.299054	40.234189	3700.0	3.5	1.68	M1	COND00	10370 ⁺¹⁸⁰⁰ ₋₂₄₀₀
841	A	292.236750	41.085899	5400.0	4.5	1.17	G9	NextGen	1170 ⁺¹⁶⁰ ₋₁₅₀
	C	292.237780	41.087064	5000.0	4.5	1.53	K1	NextGen	2120 ⁺¹⁰⁷⁰ ₋₂₇₀
	C	292.237780	41.087064	4800.0	3.5	1.46	G9	NextGen	10830 ⁺¹⁹⁰⁰ ₋₁₉₀₀
1527	A	296.671350	43.498402	5400.0	4.5	1.56	G9	NextGen	773 ⁺¹⁰³ ₋₉₈
	B	296.670978	43.500000	4800.0	4.5	2.08	K3	NextGen	1980 ⁺²²⁰ ₋₂₂₀
	B	296.670978	43.500000	4600.0	3.5	1.90	K1	NextGen	— ^d

Notes. ^(a) Calculated RA and Dec from the position of the KOI according to the distance and angle derived in this paper. ^(b) Best fit model used by VOSA. See <http://svo.cab.inta-csic.es/theory/vosa/> for more information. ^(c) Effective temperature is outside the model range ^(d) Estimated distance is greater than 21 Kpc (the estimated Milky Way limit in the *Kepler* line of sight).

stars, we computed the lower envelope of the ZAMS for both catalogs together in an i vs. $i - z$ color-magnitude diagram. Primary objects were located in the empirical ZAMS according to their $i - z$ color, which was calculated from our own photometry. Hence, a distance modulus was calculated for the primary star and applied to the secondary star assuming the joint formation of both stars. Figure 8 shows the results for all of our 17 KOIs with their 19 close stellar companions. The data for at least 6 companions agree with a simultaneous formation of stars in a double system (KOIs 0379B, 0645B, 0298B, 0641B, 0658B, and 0401B), together with the KOI star. Another three close objects could also lie within the ZAMS boundaries if we take into account the errors in the determination of this isochrone

(KOIs 0592B, 0433B and 0703B). We also note that some of them lie in the low-mass domain of the diagram, implying that KOI-0641B, KOI-0658B, KOI-0433B, and KOI-0703B could be either low-mass stars or even brown-dwarf companions to the host stars.

Brandner et al. (2000) provided a simple formula to estimate the probability that a given source at a certain angular separation to be a background object. If we assume the limiting magnitude of the USNO-B1.0⁶ catalog (Monet et al. 2003) in the *Kepler* field to be $I = 17.5$ mag, we find an overall probability of 3.9% that a source is separated 3 arcsec from our target

⁶ United States Naval Observatory.

Fig. 8. Empirical ZAMS (solid black line) computed using synthetic $i-z$ photometry from Ofek (2008), grey dots, and Moraux et al. (2003), green dots. Primary objects are represented by red filled circles and secondary companions with blue filled circles. Companions with large errors in their $i - z$ colors are plotted with blue open squares.

to be a background object. This shows, although as a first approximation, the low probability of our close companions being background sources rather than bound binaries.

Our analysis implies that 6–9 of our identified companions out of the 98 KOIs observed could be physically bound. This means an observational lower limit of 6.2%–9.2% for the binarity rate among the *Kepler* targets (the presence of binaries with projected separations or magnitudes or both below our detection limits may increase these values). However, we caution that this result may be unreliable owing to the lack of confirmation of their physical bond. We have instead shown several pieces of evidence that point to this scenario. As we have said before, it has been estimated that 20% of planets reside in binary systems that are mostly wide binaries with separations greater than 1000 AU (Thebault 2011; Desidera & Barbieri 2007; Mugrauer & Neuhäuser 2009). This would be in good agreement with our results if the physical bond were confirmed for the 6–9 KOIs mentioned above. Such widely separated companions would have weakly affected the planet formation. Desidera & Barbieri (2007) concluded that companions at separations of more than 100–300 AU would not significantly influence the formation and migration of planets and thus that planet parameters may not have relevant differences from those inhabiting single stars, except for an overabundance of high eccentricity orbits in the wide-binary planets. We do not detect any differences between the KIC-derived physical and orbital parameters of the 6–9 KOIs and those of the rest of the observed sample, confirming the results previously mentioned.

We note that our estimated binary fraction is a lower limit owing to our observational restrictions. Close and/or faint (low-mass) companions beyond our detectable limits (described in Sect. 2.3.6) might increase this multiplicity fraction. Raghavan et al. (2010) obtained a binary frequency of 34% for companions around close (<35 pc) solar-like stars in the magnitude range $V = 4$ –12. Although our present survey encompasses a different range of stellar masses, their result suggests that our study might indeed be missing a number of close and faint companions.

4.3. Need for update of planet-star parameters

The incidence among the planet and host-star parameters of either bound or visual companions to the host stars can be

measured by isolating the contribution of the host star from the blended companion. Although the transit depth defined as $F_{\text{nottransit}} - F_{\text{transit}}$ does not depend on the presence of blended objects in the PSF, the physical properties of the planet-star system actually depend on the quotient $\Delta F = (F_{\text{nottransit}} - F_{\text{transit}})/F_{\text{nottransit}}$ as shown by Seager & Mallén-Ornelas (2003). This quantity clearly decreases with the closeness of a blended object since it would contribute an additional flat flux (an intrinsic variability of the blended star would be visible in the light curve). Hence, a change in $(F_{\text{nottransit}} - F_{\text{blend}})/F_{\text{nottransit}}$ will lead to consequent changes in the planet-star parameters. Assuming that the planet is actually transiting the brighter star, the new depth will be given by (see Daemgen et al. 2009)

$$\Delta F_{\text{new}} = \left(1 + 10^{-\frac{\Delta z}{2.5}}\right) \Delta F_{\text{old}}. \quad (6)$$

We note that for the two systems where more than one blended object is found, the Δz should be computed as

$$z'_{\text{C}} = -2.5 \log \left[\sum_j 10^{-0.4z_j} \right]. \quad (7)$$

Additional photometric studies such as on-transit and out-of-transit high-resolution images of the fainter star as well as observations of the transit depth at longer wavelengths, such as with the IRAC bands of the *Spitzer* Space Telescope (see, for example, Desert et al. 2011), would be needed to rule out the possibility of the planet transiting the fainter star.

The impact on the physical parameters of a blended companion could be quite significant. The largest change in the transit depth values according to Eq. (6) is $\Delta F_{\text{new}} \leq \sqrt{2} \Delta F_{\text{old}}$, assuming an equal-magnitude blended star. According to Eq. (6) in Seager & Mallén-Ornelas (2003), this would increase the planet-to-star radius ratio by 41%. The same calculation can be done for other parameters such as the total on-transit duration (t_{T}), total on-transit flat duration (t_{F}), and period (P). We performed this exercise for our observations. Table 8 shows the recalculated values of the transit depth, planet-to-star radius ratio, and planet radius for the 24 planets orbiting the 17 stars with close companions. The last two parameters were calculated by assuming no-limb darkening, using the aforementioned formula in Seager & Mallén-Ornelas (2003) of: $R_{\text{p}}/R_{\text{s}} = \sqrt{\Delta F}$. Our results show the relative differences in the transit depths, calculated as $(\delta_{\text{new}} - \delta_{\text{cat}})/\delta_{\text{cat}}$, in the range 1%–120% from the values published by Batalha et al. (2012). According to the expression explained above, 74% of the planets with detected companions at separations of less than 3 arcsec would have changes in their $R_{\text{p}}/R_{\text{s}}$ parameter below 10%, and for 91% of them below 30%.

4.4. Particular cases

4.4.1. KOI-0641

This system is of particular interests because it is a triple visual system of size 3.7 arcsec. Its $i - z$ colors correspond to spectral types of K5-K9, M1-M3, and M3-M5 for the A, B, and C components, respectively. Regarding the SED fitting, we obtained the spectral types M2 and M3-M4 for the A and C components, respectively. The distances to the primary target for both approaches agree: they are $d = 125 \pm 22$ pc and $d = 117^{+6}_{-5}$ pc. The KOI-0641B system is perfectly consistent with the bound scenario according to its position in the ZAMS. If this scenario indeed were the case, the system would have a projected distance of 275 ± 49 AU from the A component. The third object is

Table 8. New planet-transit depth and relative radii to the parent star accounting for the blended objects in the *Kepler* images.

Planet ID (KOI.Planet)	Cat. Depth (ppm)	NewDepth (ppm)	Cat R_p/R_* (10^{-2})	New R_p/R_* ^a (10^{-2})	Sec. R_p/R_* ^b (10^{-2})	Cat. R_p ^c R_{Earth}	New R_p ^d R_{Earth}
298.01	274	472 ± 67	1.41 ± 0.04	2.2 ± 0.2	2.6 ± 0.3	1.40	2.16
379.01	292	422 ± 24	1.6 ± 0.1	2.1 ± 0.1	3.1 ± 0.2	2.58	3.38
379.02	136	196 ± 11	1.1 ± 0.1	1.40 ± 0.04	2.1 ± 0.1	1.83	2.31
387.01	1122	1137 ± 75	3.3 ± 0.3	3.4 ± 0.1	29.4 ± 73.4	2.18	2.23
401.01	2103	2363 ± 132	4.1 ± 0.2	4.9 ± 0.1	13.8 ± 3.1	6.57	7.82
401.02	1618	1818 ± 101	4.2 ± 0.2	4.3 ± 0.1	12.1 ± 2.7	6.67	6.85
433.01	2864	3048 ± 76	5.10 ± 0.04	5.5 ± 0.1	21.8 ± 4.2	5.60	6.06
433.02	13690	14570 ± 365	11.7 ± 0.1	12.1 ± 0.2	47.6 ± 9.3	12.90	13.27
592.01	539	561 ± 19	2.6 ± 0.1	2.37 ± 0.04	11.7 ± 4.9	2.74	2.48
626.01	374	378 ± 4	1.8 ± 0.1	1.94 ± 0.01	19.2 ± 8.7	2.09	2.30
628.01	476	504 ± 21	2.2 ± 0.2	2.24 ± 0.05	9.3 ± 3.4	1.87	1.90
641.01	1002	2225 ± 90	3.1 ± 1.3	4.7 ± 0.1	4.3 ± 0.1	1.83	2.82
644.01	23950	30367 ± 591	13.87 ± 0.03	17.4 ± 0.2	33.7 ± 1.2	33.16	41.67
645.01	201	239 ± 5	1.61 ± 0.05	1.55 ± 0.02	3.6 ± 0.2	2.53	2.44
645.02	257	305 ± 7	1.59 ± 0.03	1.75 ± 0.02	4.0 ± 0.2	2.51	2.75
658.01	505	517 ± 8	2.1 ± 0.1	2.27 ± 0.02	14.7 ± 5.0	2.03	2.18
658.02	484	496 ± 8	2.1 ± 0.1	2.23 ± 0.02	14.4 ± 4.9	2.02	2.13
658.03	166	170 ± 3	1.2 ± 0.1	1.30 ± 0.01	8.5 ± 2.9	1.14	1.25
703.01	130	131 ± 1	1.04 ± 0.05	1.142 ± 0.003	17.9 ± 12.1	1.36	1.50
721.01	276	284 ± 2	1.63 ± 0.03	1.685 ± 0.007	9.9 ± 1.4	2.76	2.86
841.01	2967	3071 ± 45	5.4 ± 0.1	5.54 ± 0.04	29.6 ± 6.3	5.44	5.56
841.02	4962	5136 ± 7	7.0 ± 0.2	7.2 ± 0.1	38.3 ± 8.1	7.05	7.19
1375.01	2608	2651 ± 99	5.3 ± 0.6	5.1 ± 0.1	40.0 ± 44.8	6.65	6.44

Notes. In this calculation, we have taken into account only the closest objects (<3 arcsec) to the KOI. KOI-0704.01 is not present owing to the large errors in its Δz value. ^(a) New planet-to-star radii ratio assuming no limb-darkening. ^(b) Planet-to-star radius assuming that the host is actually the secondary companion detected at less than 3 arcsec. ^(c) Planet radii calculated by the Kepler team (Batalha et al. 2012). ^(d) Planet radii assuming the new depth and no limb-darkening. No error is presented since no error in the stellar radii is given.

located well above the empirical ZAMS (~3 mag brighter), indicating that it is probably a foreground M-dwarf. This hypothesis agrees with the distance calculated by the SED fitting approach, $d = 76^{+15}_{-10}$, which is significantly closer than the A component.

4.4.2. KOI-0433

The companion to KOI-0433 is too faint and red for clear conclusions to be extracted about its nature. Our analysis suggests that it is a $M5^{+1}_{-2}$ star probably bound to the main KOI. However, the primary target is also too faint ($m_i > 14.5$) and the large errors in the distance do not allow us to set constraints on the projected separation of the system. Nevertheless, owing to the position of the secondary object in the Hertzsprung-Russell (HR) diagram of Fig. 8, as in KOI-0641C, there may be a third component very close to KOI-0433B that is unresolved in our images. Hence, we consider this object as a possible false positive, although more observations need to be done.

4.4.3. KOI-0298

The projected distance estimated for the assumed primary target is 118 ± 18 pc according to Sect. 8. The stellar companion to this KOI has a $i - z$ color typical of early M dwarfs. Its position in the M_i vs. $i - z$ diagram is in good agreement with a simultaneous formation of both objects. Thus, a relative separation of 231 ± 35 AU is derived for the possible binary system. Moreover, since both objects have very similar magnitudes, it is unclear which star is actually hosting the transient object. There is also a third very faint object in the SDSSi image, which is not detected in the SDSSz image acquired a few hours later in the same night probably because it is a background blue object.

4.4.4. KOI-0379

The projected distance of this object was estimated to be 244 ± 76 pc. Its possible companion, which has a spectral type earlier than K5, would be located, if bounded, at 463 ± 165 AU from the primary target. However, since these estimations were based on photometric values and the corresponding night was not photometric, we caution that the true errors are probably larger than the ones provided here.

4.4.5. KOI-0645

KOI-0645 is a two-planet candidate system. The location of the secondary star in the HR diagram suggests that it is physically bound to the candidate host star. Its estimated distance of 328 ± 82 pc corresponds to a relative separation of 910 ± 228 AU.

4.4.6. KOI-0401

This is another star presumably hosting two planets. The stellar companion has been estimated to be a K9 star at a projected distance of 590 ± 190 AU assuming that the distance of 302 ± 98 pc derived for the primary is correct.

4.4.7. KOI-0623

The nature of the stellar companion at 5.54 arcsec from the KOI-0623 still remains unclear in this work. Both of the possible assumptions of luminosity classes are suitable. If it were a giant K2 background star, it should be at 790^{+250}_{-350} pc. If it were instead a dwarf it may be bound to the A component since they are very close to each other despite lying outside the margins of error.

4.4.8. KOI-0658

This is a very faint companion with an approximate spectral type of M3 that was detected close to this KOI. Owing to its faintness, large errors are present in the determination of its projected distance, which is 790 ± 330 AU based on a 420 ± 180 pc distance from the primary. Moreover, since $\Delta m_z \approx 4.06$, the planet properties of the two transient objects to the KOI are almost unaffected.

4.4.9. KOI-0703

This is the faintest close companion detected in our sample. A less significant than $3\text{-}\sigma$ detection was achieved for this companion so that the results for this object may be carefully used.

4.4.10. KOI-1375 and KOI-0387

A very close visual stellar companion was detected for these KOIs. In the case of KOI-1375, the object seems to be bluer than the KOI, suggesting that it is probably a background object. The companion of KOI-0387 has the same $i-z$ color, hence, if we assume that they have the same age we conclude that they also have similar spectral types. However, the KOI is several magnitudes brighter and redder than the companion, implying that it is most likely a background close companion. We also note that observations of KOI-0387 were performed during a non-photometric night. Very large errors were found owing to both the faintness and closeness of both objects to their corresponding KOIs.

5. Conclusions

We have started a high-resolution imaging follow-up of *Kepler* planet-host candidates. The main goal of this survey has been to provide additional confirmation of the planetary nature of these candidates and identify which are possible false positives. A total of 98 KOIs (out of the 997) from the second release of the *Kepler* team were observed using the lucky imaging technique with the AstraLux instrument at the 2.2 m telescope at Calar Alto Observatory.

Our main results show that the 58.2% of the KOIs are actually isolated in terms of not having any visual or bounded companion within 6 arcsec. In other words, 41.9% of the candidates have nearby objects. This is important for the following results: (a) false-positive rate determination, since it points directly to objects with stellar companions possibly mimicking a planet transit detected by *Kepler*, which are then the highest priority for a deeper follow-up with ground-based telescopes to determine the nature of this transit; (b) updating the planet properties, since as we have shown in Sect. 4, these depend on the brightness of the host star. We caution that the orbital and physical parameters of the 23 planets orbiting the 17 KOIs with close stellar companions should be revised; (c) estimating the binary rate in planet-host stars. According to their position on a M_i vs. $i-z$ color-magnitude diagram, we have shown that between 6 and 9 of the close companions could actually be bound to the host star owing to their position in our empirical ZAMS. Their distances agree with those of an S-type binary, although more observations are necessary to confirm both the planet and the binary in all cases. The KOIs 0379B, 0658B, 0641B, 0645B, and 0298B clearly lie in the ZAMS, which suggests that they simultaneously formed with their primary stars. Moreover, the

KOIs 0433B, 0401B, 0592B, and 0703B could also lie inside the error bars of the ZAMS although more work is needed to confirm this result. If confirmed, this would imply a lower limit to the observed binary frequency of 6.2–9.2%. For the medium-distance companions (3–6 arcsec), we found that only one of them (KOI-0623B) is possibly bound although this result may be unreliable owing to the large errors in the distance estimates.

Finally, we have provided accurate astrometric positions and i magnitudes for the close and medium-distance companions, which could be used to re-compute planet-star parameters in the KOIs affected by the light of the companion. These results provide tighter constraints on theoretical studies of the false positive probabilities for the particular objects studied in this paper.

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