ROBO-AO *KEPLER* PLANETARY CANDIDATE SURVEY. II. ADAPTIVE OPTICS IMAGING OF 969 *KEPLER* EXOPLANET CANDIDATE HOST STARS

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ABSTRACT

We initiated the Robo-AO *Kepler* Planetary Candidate Survey in 2012 to observe each *Kepler* exoplanet candidate host star with high angular resolution, visible light, laser adaptive optics (AOs) imaging. Our goal is to find nearby stars lying in *Kepler*'s photometric apertures that are responsible for the relatively high probability of false-positive exoplanet detections and that cause underestimates of the size of transit radii. Our comprehensive survey will also shed light on the effects of stellar multiplicity on exoplanet properties and will identify rare exoplanetary architectures. In this second part of our ongoing survey, we observed an additional 969 *Kepler* planet candidate hosts and we report blended stellar companions up to $\Delta m \approx 6$ that contribute to *Kepler*'s measured light curves. We found 203 companions within $\sim 4''$ of 181 of the *Kepler* stars, of which 141 are new discoveries. We measure the nearby star probability for this sample of *Kepler* planet candidate host stars to be $10.6\% \pm 1.1\%$ at angular separations up to $2''.5$, significantly higher than the $7.4\% \pm 1.0\%$ probability discovered in our initial sample of 715 stars; we find the probability increases to $17.6\% \pm 1.5\%$ out to a separation of $4''.0$. The median position of *Kepler* Objects of Interest (KOIs) observed in this survey are $1^\circ.1$ closer to the galactic plane, which may account for some of the nearby star probability enhancement. We additionally detail 50 Keck AO images of Robo-AO observed KOIs in order to confirm 37 companions detected at a $<5\sigma$ significance level and to obtain additional infrared photometry on higher significance detected companions.

Key words: binaries: close – instrumentation: adaptive optics – instrumentation: high angular resolution – planetary systems – planets and satellites: detection – planets and satellites: fundamental parameters

Supporting material: machine-readable table

1. INTRODUCTION

The primary *Kepler* mission photometrically observed approximately 200,000 stars for 4 years in the search for transiting exoplanets. As of the Q1-Q17 DR24 data set release (Coughlin et al. 2015), there are 3,324 *Kepler* Objects of Interest (KOI) stars in the *Kepler* input catalog that are designated as either “CONFIRMED” or “CANDIDATE” in the NASA Exoplanet Archive (Akeson et al. 2013), with 4302 repeating transit signals indicative of transiting exoplanets. While *Kepler* is one of the best facilities to measure the periodic dips in stellar brightness caused by transiting exoplanets, it has a coarse pixel size, $\sim 4''$, and a mean 95% encircled energy diameter of 4.3 pixels (Haas et al. 2010) that make it unsuitable for reliably detecting multiple sources within the *Kepler* photometric apertures. Follow-up high angular resolution imaging of KOIs is used to determine the sources contributing to the *Kepler* light curves in order to rule out astrophysical false-positives (e.g., Morton & Johnson 2011; Dressing & Charbonneau 2013; Fressin et al. 2013; Santerne et al. 2013), to accurately measure the radii of the detected planets with respect to their host star (e.g., Campante et al. 2015; Ciardi et al. 2015), to measure the effect of stellar multiplicity on exoplanet formation (e.g., Wang et al. 2014a, 2014b, 2015a, 2015b), and to study other astrophysical phenomena (e.g., Muirhead et al. 2013; Montet et al. 2015).

In 2012, we initiated the Robo-AO *Kepler* Planetary Candidate Survey in an effort to systematically observe each *Kepler* planet candidate host star in a consistent way with adaptive optics (AO). No AO survey of this magnitude had previously been attempted and this type of survey has only recently been made possible with the commissioning of the Robo-AO robotic laser AO system that can observe more than 200 objects in a single night (Baranec et al. 2014a). We expect that the results of this survey will be used in validating candidate exoplanets, correcting the estimates of transit radii, identifying rare and interesting exoplanetary system architectures, and exploring the properties and trends of exoplanets in multiple star systems.

During our first observing season in 2012, we observed 715 KOIs with Robo-AO (Law et al. 2014, henceforth Paper I). Of the 715 KOIs observed, we found 53 to have a fainter stellar companion within a $2''.5$ radius, leading to a nearby star probability of $7.4\% \pm 1.0\%$. We now report results from the second part of our ongoing survey, comprising a further 969 observations of KOIs with Robo-AO. We additionally report Keck AO images of 50 of the Robo-AO observed KOIs to confirm companion detections made at low significance, $<5\sigma$, and to obtain additional infrared photometry that will later be used to better constrain photometric parallaxes to determine if the companions are physically associated (D. Atkinson et al. 2016, in

Figure 1. Comparison of the distribution of the Robo-AO sample in this paper, from Q1-Q12 (Rowe et al. 2015), to the set of KOIs from Q1-Q17 DR24 (Coughlin et al. 2015).

preparation). Of the 969 KOIs observed, we have found 203 companions,⁷ of which 141 are new discoveries.

This paper is organized as follows. In Section 2 we describe the KOI survey target selection and the observations made with Robo-AO and NIRC2. Sections 3 and 4 describe the Robo-AO and NIRC2 data reduction and companion detection pipelines, respectively. In Section 5 we describe the results of the survey, including the companions discovered, and compare these with other surveys and observations. In Section 6 we discuss implications of the survey and how others can use these observations. Finally, we conclude with plans for current and future work in Section 7.

2. SURVEY, TARGETS, AND OBSERVATIONS

2.1. Target Selection

We selected targets that we had not previously observed from the KOI Catalog based on the Q1-Q12 *Kepler* data (Rowe et al. 2015). These targets were added to the Robo-AO intelligent observing queue (Riddle et al. 2014) and observed during the summer of 2013. While we imposed no artificial magnitude limit on the targets, there were only four targets

fainter than the 16th magnitude that we effectively observed. In Figure 1 we compare the Robo-AO imaged KOIs to the distribution of all current KOIs (Coughlin et al. 2015). The four graphs show the comparisons in the characteristics of KOI stellar magnitude and effective temperature, and planetary orbital period and radius. The list we have observed correlates closely with the *Kepler* Q1-Q17 DR24 list in all of these categories, with the exception of the longest period planets, which are fewer in number in the Q1-Q12 list due to the shorter time baseline. It is only by coincidence that we did not observe the small number of KOIs with 15–20 $R_{\oplus}$ companions or with stellar temperatures higher than 8000 K.

2.2. Observations

2.2.1. Robo-AO

We obtained high angular resolution images of 956 *Kepler* planet candidate host stars over the course of 19 nights between 2013 July 21 and 2013 October 25, detailed in Table 5 in the Appendix. We also include 13 images from 2012 that required additional confirmation of the KOI position in the Robo-AO field of view. All the observations were performed in a queue-scheduled mode in combination with other science programs using the Robo-AO autonomous laser AO system (Baranec et al. 2013, 2014a) mounted on the robotic 1.5 m telescope at

⁷ For brevity, we denote stars which we have found within our detection radius of KOIs as “companions,” in the sense that they are asterisms associated on the sky.

Table 1
Specifications of the Robo-AO KOI survey

KOI targets	969
Exposure time	90 s
Observation wavelengths	600–950 nm
FWHM resolution	0"12–0"15
Field of view	44" × 44"
Pixel scale	43.1 mas/pix
Detector format	1024 ² pixels
Observation dates	2012 July 16–September 13 2013 July 21–October 25
Targets observed/hour	20

Palomar Observatory (Cenko et al. 2006). Table 1 summarizes the system and survey specifications.

Each observation comprises a sequence of full frame transfer detector readouts of an electron multiplying CCD camera at the maximum rate of 8.6 Hz. Individual frames are later registered to correct for the dynamic image displacement of the KOI (Section 3) that cannot be measured with the laser guide star. A total exposure integration time of 90 s was chosen so that close sources up to roughly 6 magnitudes fainter than the *Kepler* object would be detected. For the majority of these observations, a long-pass filter with a cut on wavelength of 600 nm was used (LP600 hereafter). The LP600 filter approximately matches the *Kepler* passband at the redder wavelengths while simultaneously suppressing the blue wavelengths. The blue wavelengths will degrade the performance of AOs in the majority of seeing conditions. Compared to near-infrared AO observations, the LP600 filter more closely approximates the direct measurement of the effects of any unresolved companions for the relevant *Kepler* light curves. An *i'*-band filter (York et al. 2000) was used during eight of the 2012 observations in an attempt to obtain slightly sharper images of brighter targets. A comparison of the two filters can be found in Paper I.

There are two main factors that affect the quality of images acquired by Robo-AO: atmospheric seeing and the brightness of the target. For bright targets ($m_V < 13$), in a median seeing of 1"1 (Cenko et al. 2006), Robo-AO can obtain images with a Strehl ratio of 9% and FWHM of 0"12 in the *i'* band. As the seeing approaches 1"6, the Strehl ratio drops to 5%. For fainter targets, i.e., $m_V > 14$, there needs to be a sufficient number of photons in the diffraction-limited core captured during each frame transfer exposure for post-facto image registration techniques to maintain full acuity. Robo-AO is able to capture scientifically useful images on these fainter targets during times when the atmospheric seeing is favorable, so observations are often repeated until data of sufficient quality is obtained. We adopted the same automated routines used by Paper I to measure the actual imaging performance and to classify the targets into the imaging performance classes given in the full observations list; this classification was used with the contrast curve for each class to estimate the companion detection performance for each target (Section 3.5).

2.2.2. Keck AOs

We obtained images of 50 KOIs with the NIRC2 instrument behind the Keck II AO system that were previously observed with Robo-AO and had evidence of a companion. For KOIs brighter than $m_V \sim 13$, we typically used the KOI as the guide star in natural guide star mode, and for fainter KOIs we used

the laser guide star, using the KOI as the tip-tilt focus guide star (Wizinowich et al. 2006; van Dam et al. 2006). Observations were conducted on 2013 June 25, 2013 August 24 and 25, 2014 August 17, and 2015 July 25 in the K, Ks, or Kp filters, and in the narrow mode of NIRC2 (9.952 mas pixel⁻¹; Yelda et al. 2010). An initial 30 s exposure was taken for each target, and we waited for the low-bandwidth wavefront sensor to settle if the laser was used. The integration time and number of co-adds per detector readout were adjusted to keep the peak of the stellar point-spread function (PSF) counts less than 8,000 ADU per single integration (roughly half the dynamic range where sensitivity of the detector is linear), while maintaining a total exposure time of 30 s. Dithered images were then acquired with the primary centered in the 3 lowest noise quadrants using the “bxy3 2.5” command, for a total exposure time of 90 s.

3. ROBO-AO DATA REDUCTION

We adopted the same automated data reduction and analysis pipeline used in Paper I and we briefly review it here, along with minor improvements. We first manually find the location of the KOI in the field using a preliminary reduction of the data (Section 3.1). The pipeline first takes the short-exposure data cubes recorded by the electron multiplying CCD camera and produces dark, flat-field, and tip-tilt-corrected co-added output images (Section 3.2). We then subtract a locally optimized PSF estimate from the image of the *Kepler* target in each field (Section 3.3), and either detect companions around the target stars or place limits on their existence (Section 3.4). Finally, we measure the properties of the detected companions (Section 3.6).

3.1. Target Confirmation

We manually checked the location of the KOI in Digital Sky Survey (DSS) images and selected the KOI itself as the guide star to correct image displacement in each observation. In this survey, for fields where the DSS image was insufficient for KOI identification, or if the proper motion of stars made the target ambiguous, we would use the publicly available recent UKIRT J-band images of the *Kepler* field. For a minority of targets, there was only a single star in the field of view. For these targets, we first confirmed with UKIRT images that there were no other sources within our field; then we confirmed whether the telescope pointing offsets were stable for that particular observation by noting if prior and subsequent KOI targets landed in the same area of the detector. We note that Paper I did not include all of the observed targets in 2012 because of our inability to unambiguously identify every KOI. Using this new method of target confirmation, we were able to positively identify 13 KOIs observed in 2012 and now include them in this paper.

3.2. Imaging Pipeline

The Robo-AO imaging pipeline (Law et al. 2012; Terziev et al. 2013) is based on the lucky imaging reduction system described in Law et al. (2006a, 2006b, 2009). The recorded camera frames are dark-subtracted and flat fielded, and are then corrected for image displacement using the KOI as the reference guide star. This produced more consistent and predictable imaging performance for groups of similar KOIs, even if a brighter guide star was nearby and offered potentially increased performance.

Figure 2. Points on this plot show the angular separations and magnitude differences of the detected companions described in Tables 2 and 3, with the color and shape of each point denoting the associated typical low-, medium-, and high-performance 5σ contrast curve during the observation (as described in Section 3.5).

3.3. PSF Subtraction

The large number of KOI target stars observed each night are all in similar parts of the sky, have similar brightness, and were observed at similar airmasses. We take advantage of this fact and use each night’s KOI observations as PSF references due to the fact that it is unlikely that a companion would be in the same position for multiple targets. We use a custom locally optimized PSF subtraction routine based on the Locally Optimized Combination of Images algorithm (Lafrenière et al. 2007), wherein the regions around at least 20 targets are combined to create a PSF which is an optimal local combination of the reference PSFs and is then subtracted from the target star’s PSF. The PSF subtraction typically leaves residuals that are consistent with photon noise only (for these relatively short exposures). For more information and an example of the target star subtraction, see Paper I.

3.4. Automated Companion Detection

To more easily and robustly find companions in this large data set, we developed a new automated companion detection algorithm for Robo-AO data, described in Paper I. During the analysis of images for this survey, we extended the automated search radius from $2''.5$ to $4''.0$ to capture a larger population of stars that contribute to the *Kepler* light curves, as well as to facilitate better comparison with other high angular resolution imaging surveys.

We also manually checked each image for companions after the automated companion detection to assess the performance of the automated system and to search for faint but real companions that could have been removed by spurious speckles in the PSF references. Only those that had a measured significance of $>2.0\sigma$ are reported here despite the fact that others may have confirmed their existence (e.g., the $\sim 0''.5$ companions detected near KOI-3284 and KOI-3309). While not comprehensive, we also flagged several low-significance companions out to $\sim 4''.5$ that were just outside of the automatic search radius during the manual check.

3.5. Imaging Performance Metrics

In Paper I, we evaluated the contrast versus radius detection performance of the PSF subtraction and automated companion detection code by performing Monte Carlo simulations of artificial companion injection and recovery. We found that if we fit two Moffat functions to each PSF, one tuned to the PSF core and the other to the uncorrected halo, that the width of the PSF core size alone was an excellent predictor of contrast performance. On this basis, we used the PSF core size to assign targets to contrast performance groups: “low,” $<0''.1$, $N = 355$; “medium,” $[0''.1, 0''.14)$, $N = 308$; and “high,” $\geq 0''.14$, $N = 306$. Figure 2 shows smoothed contrast curves resulting from the Monte Carlo companion detection simulations for the three ranges of contrast performance groups.

3.6. Companion Contrast Ratios, Separations, and Position Angles

We determined the contrast ratio between the companions and primaries in two ways: for the widest separations, we performed aperture photometry on the original images; for the closer systems, we used the estimated PSF to remove the blended contributions of each of the stars before performing aperture photometry. In all cases, the aperture sizes were optimized for the system separation and the available signal. We calculated the contrast ratio uncertainty on the basis of the difference between the injected and measured contrasts of the artificial companions during the contrast curve calculations (Section 3.4). We found that the detection significance of the companion was the best predictor of the contrast ratio accuracy, and so we use that relation to estimate the contrast ratio uncertainty for each companion. We note that the uncertainties (5%–30%) are much higher than would be naively expected from the signal-to-noise ratio of the companion detection, as they include an estimate of the systematic errors resulting from the AO imaging, PSF subtraction, and contrast measurement processes.

To obtain the separation and position angle of the binaries, we measured the centroid of the PSF-subtracted images of the companion and primary, as above. We converted the raw pixel

positions to on-sky separations and position angles using a distortion solution produced from Robo-AO measurements of globular clusters, detailed in Riddle et al. (2015). We calculated the uncertainties of the companion separation and position angles using estimated systematic errors in the position measurements due to blending between components, depending on the separation of the companion (typically 1–2 pixels uncertainty in the position of each star). We also included an estimate of the maximal changes in the Robo-AO orientation throughout the observation period ($\pm 1.5^\circ$), as verified using the globular cluster measurements above. Finally, we verified the measured positions and contrast ratios in direct measurement from non-PSF-subtracted images.

4. NIRC2 DATA REDUCTION

We created a pipeline to automatically reduce and analyze our NIRC2 data. After sky subtraction and flat-field calibration, the frames were co-added into a single image based on the automatic detection of the location of the primary star in each dither frame. Because the distortion across each detector quadrant is sufficiently small compared to the Robo-AO position errors, ≤ 20 mas (Yelda et al. 2010), we did not correct for field distortion. The pipeline then automatically identifies companion stars via pixel binning, vetting the brightest bins by measuring radius in the eight cardinal and diagonal directions against a minimum cutoff and radial consistency. Cutoff values are optimized to search for both wide and narrow separation companions. For targets with observations in multiple filters (reported in D. Atkinson et al. 2016, in preparation), the results are cross-referenced and stars found in only one filter are dropped as multi-color observations are effective in discriminating PSF speckles from astrophysical objects. Targets for which the pipeline registered multiple companions are flagged for manual validation.

The higher angular resolution images clearly separate the vast majority of companions and simple aperture photometry is used to measure the brightness of each star. For close companions, a matching aperture opposite the partner star from the object being investigated is subtracted from the star’s own photometry. This corrects for any overlapping PSF halo (and assumes a radially constant PSF, which is more accurate at larger separations). Magnitude differences between companions and their primary star are shown in Table 4.

The uncertainty in the magnitude difference is estimated by varying the aperture radius from 0.5 to 5 of the width of the stellar PSF and measuring the standard deviation of the difference. Injected companions are used to measure the overall efficacy of the technique and determine the weighting of magnitude difference versus aperture radius. Recovering injections with this technique demonstrated an uncertainty of $\sim 5\%$, consistent with our reported uncertainties.

5. DISCOVERIES

We resolved 181 *Kepler* planet candidate hosts into multiple stars; the contrast ratios and the separations are shown in Figure 2 and the discovery images are summarized in Figures 3–5. The measured companion properties for the targets with secure detections, $>5\sigma$, are detailed in Table 2. Table 3 describes probable companions which fell just below our formal 5σ detection criteria. We consider these very likely to be real, but we cannot exclude the possibility that a small

fraction of these detections are spurious speckles without additional information. Where possible, we observed these targets with NIRC2 to confirm their existence, as discussed in Section 5.3.

5.1. Comparison to Other Imaging Surveys

In the search for blended *Kepler* companions, many other high angular resolution surveys of KOIs have been performed using a range of observational techniques, e.g., infrared AOs, sparse aperture interferometry, speckle interferometry, lucky imaging, and direct imaging with the *Hubble Space Telescope* (*HST*; Howell et al. 2011; Adams et al. 2012, 2013; Horch et al. 2012; Lillo-Box et al. 2012, 2014; Dressing et al. 2014; Marcy et al. 2014; Everett et al. 2015; Gilliland et al. 2015; Teske et al. 2015; Torres et al. 2015; Wang et al. 2015a, 2015b; Gaidos et al. 2016; Kraus et al. 2016). Each technique and instrument setup has a unique sensitivity, inner working angle, and spectral bandpass, presenting a challenge for a complete analysis of the multiplicity of KOI stars, and is part of our motivation for observing all KOIs with a single instrument setup. We have indicated in Tables 2 and 3 where these surveys have previously detected the same companion at approximately the same location. These other surveys have detected 38 of the 98 companions we detected at a significance greater than 5σ , and 24 of the 105 companions we detected at a lower significance.

Interestingly, Robo-AO was able to detect a close companion to KOI-2971 at a significance of 3.9σ that was not detected by Dressing et al. (2014) using ARIES with the MMT AO system; and conversely Robo-AO did not detect the $3''.5$ companion found by Dressing et al. (2014). We fortuitously observed KOI-2971 with NIRC2 (see Section 5.3) and we were able to clearly see both of these companions.

We also note that the Robo-AO automated companion detection software found companions to KOI-2849 and KOI-3246 at nearly the same separation, $0''.36$, position angle, 215° , magnitude difference, ~ 1 , and at a significance level of 4.0σ and 5σ , respectively. Observations of both targets occurred on 2013 August 16 and showed evidence of static non-common path error in the stellar PSF leading to a speckle in the position of the purported companions. Kraus et al. (2016) observed KOI-3246 with NIRC2, and confirmed that there was no companion of similar brightness near the location of the Robo-AO automated detection. Because of our insensitivity at that position during that night, we did not report these detections in our list of companions.

5.2. Comparison to a Spectroscopic Survey

Kolbl et al. (2015) searched for close companions to KOIs by detecting secondary light sources in spectra used for determining radial velocities. They demonstrated sensitivity to companions as faint as $\sim 1\%$ of the primary star, and to companions captured within the $0''.87 \times 3''.0$ Keck-HIRES entrance slit. We observed 19 of the 58 KOIs for which Kolbl et al. (2015) found evidence for a companion. Of those 19, we detected companions to KOI-151, KOI-652, KOI-1784, and KOI-4871. We had sufficient image contrast performance for the other 15 targets, 12 “high” and 3 “medium,” to detect the brightness of the companion indicated by Kolbl et al. (2015) if they were separated by greater than roughly $0''.75$; this lends

Figure 3. Color-inverted, normalized log scale cutouts of 61 multiple KOI systems [KOI-4 to KOI-2056] with separations $<4''$ resolved with Robo-AO. The angular scale and orientation is similar for each cutout. The smaller circles are centered on the detected nearby star.

Figure 4. Color-inverted, normalized log-scale cutouts of 61 multiple KOI systems [KOI-2067 to KOI-3277] with separations $<4''$ resolved with Robo-AO. The angular scale and orientation is similar for each cutout. The smaller circles are centered on the detected nearby star.

Figure 5. Color-inverted, normalized log-scale cutouts of 59 multiple KOI systems [KOI-3284 to KOI-4871] with separations $<4''$ resolved with Robo-AO. The angular scale and orientation is similar for each cutout. The smaller circles are centered on the detected nearby star.

Table 2
 Detections of Objects Within $\sim 4''$ of *Kepler* Planet Candidates at $\geq 5\sigma$ Significance

KOI	m_i (mag)	ObsID	Filter	Signf. σ	Separation (arcsec)	P.A. (deg.)	Mag. Diff. (mag)	Previous Detection?	NIRC2 Detection?
KOI-4	11.3	2012 Jul 16	i'	12	3.42 ± 0.06	75 ± 2	4.46 ± 0.05	...	...
KOI-42	9.2	2013 Jul 28	LP600	35	1.74 ± 0.06	35 ± 2	3.04 ± 0.17	A12, H11, K16	...
KOI-227	13.7	2013 Jul 27	LP600	5	0.33 ± 0.06	72 ± 6	0.84 ± 0.09	H11, K16	...
KOI-258	9.8	2012 Jul 18	i'	14	1.05 ± 0.06	77 ± 2	2.76 ± 0.17	A12, H11	...
KOI-284	11.7	2013 Jul 27	LP600	19	0.96 ± 0.06	98 ± 2	0.45 ± 0.04	A12, H11, E15, K16	...
KOI-298	12.4	2013 Aug 15	LP600	477	2.11 ± 0.06	270 ± 2	0.58 ± 0.04	LB12, K16	...
KOI-379	13.2	2013 Jul 27	LP600	56	2.11 ± 0.06	83 ± 2	1.42 ± 0.11	LB12	...
KOI-521	14.5	2013 Aug 14	LP600	18	3.24 ± 0.06	152 ± 2	0.42 ± 0.03	...	...
KOI-558	14.6	2013 Aug 22	LP600	6	3.16 ± 0.06	271 ± 2	2.06 ± 0.04	...	...
KOI-641	13.1	2013 Jul 24	LP600	18	2.09 ± 0.06	278 ± 2	2.07 ± 0.05	LB12	...
				46	3.65 ± 0.06	205 ± 2	0.33 ± 0.06	LB12	...
KOI-645	13.5	2013 Jul 25	LP600	6	2.98 ± 0.06	48 ± 2	2.23 ± 0.04	LB12	...
KOI-652	13.3	2013 Jul 28	LP600	21	1.23 ± 0.06	272 ± 2	1.59 ± 0.14	K15, K16, Te15	...
KOI-697	13.5	2013 Aug 15	LP600	9	0.71 ± 0.06	54 ± 3	0.06 ± 0.03	W15	...
KOI-801	14.8	2013 Oct 25	LP600	6	3.67 ± 0.06	195 ± 2	2.58 ± 0.11	...	...
KOI-976		2012 Aug 03	i'	22	0.25 ± 0.06	129 ± 7	0.34 ± 0.09	K16	...
KOI-1061	14.3	2013 Aug 20	LP600	14	1.22 ± 0.06	38 ± 2	1.21 ± 0.07	...	...
KOI-1300	13.9	2013 Aug 16	LP600	8	0.78 ± 0.06	357 ± 3	1.79 ± 0.18	K16	...
KOI-1357	15.3	2013 Aug 18	LP600	30	3.83 ± 0.06	167 ± 2	3.38 ± 0.03	...	...
KOI-1531	12.9	2013 Aug 16	LP600	7	0.43 ± 0.06	99 ± 4	0.90 ± 0.16	...	...
KOI-1546	14.2	2013 Aug 19	LP600	6	0.62 ± 0.06	86 ± 3	1.03 ± 0.12	LB14	yes
KOI-1717	14.3	2013 Oct 25	LP600	9	0.87 ± 0.06	305 ± 3	1.46 ± 0.13	...	...
KOI-1853	13.3	2013 Aug 14	LP600	11	0.96 ± 0.06	304 ± 2	0.24 ± 0.05	...	...
KOI-1861	13.8	2013 Jul 28	LP600	5	2.10 ± 0.06	84 ± 2	4.93 ± 0.16	...	...
KOI-1899	14.4	2013 Jul 27	LP600	16	1.84 ± 0.06	342 ± 2	0.94 ± 0.05	...	...
KOI-1972	13.6	2013 Aug 15	LP600	21	1.05 ± 0.06	246 ± 2	1.05 ± 0.12	...	...
KOI-2032	12.0	2013 Jul 28	LP600	17	1.19 ± 0.06	317 ± 2	0.34 ± 0.05	K16	...
KOI-2067	12.3	2013 Jul 24	LP600	17	1.64 ± 0.06	315 ± 2	0.80 ± 0.04	K16	...
KOI-2096	14.9	2013 Aug 19	LP600	29	3.50 ± 0.06	17 ± 2	4.13 ± 0.11	...	...
KOI-2098	13.7	2013 Jul 27	LP600	8	2.88 ± 0.06	156 ± 2	2.58 ± 0.04	...	...
				10	3.24 ± 0.06	132 ± 2	2.40 ± 0.06	...	...
KOI-2100	14.4	2013 Jul 28	LP600	8	2.98 ± 0.06	318 ± 2	2.10 ± 0.05	...	...
KOI-2174	15.2	2012 Aug 07	LP600	10	0.92 ± 0.06	226 ± 2	0.21 ± 0.06	...	...
				25	3.88 ± 0.06	314 ± 2	0.14 ± 0.03	...	...
KOI-2295	11.4	2013 Jul 29	LP600	21	2.19 ± 0.06	78 ± 2	0.88 ± 0.06	K16	...
KOI-2298	13.5	2013 Aug 16	LP600	29	1.57 ± 0.06	194 ± 2	2.08 ± 0.14	D14	...
KOI-2377	14.5	2013 Jul 24	LP600	14	2.09 ± 0.06	335 ± 2	1.25 ± 0.03	...	yes
KOI-2421	14.0	2013 Jul 25	LP600	8	1.23 ± 0.06	290 ± 2	0.99 ± 0.09	D14	...
KOI-2474	13.9	2013 Aug 13	LP600	8	0.61 ± 0.06	279 ± 3	0.65 ± 0.07	H12	...
KOI-2598	14.0	2013 Aug 13	LP600	9	1.09 ± 0.06	75 ± 2	0.37 ± 0.04	...	...
KOI-2601	13.8	2013 Aug 13	LP600	17	1.66 ± 0.06	14 ± 2	1.43 ± 0.06	...	...
KOI-2679	13.3	2013 Jul 25	LP600	19	2.11 ± 0.06	324 ± 2	2.87 ± 0.06	...	...
KOI-2705	14.3	2013 Jul 25	LP600	15	1.84 ± 0.06	304 ± 2	3.19 ± 0.14	G16, K16	yes
KOI-2711	13.5	2013 Jul 29	LP600	8	0.52 ± 0.06	147 ± 4	0.12 ± 0.08	...	yes
KOI-2729	13.7	2013 Aug 18	LP600	6	3.94 ± 0.06	278 ± 2	2.03 ± 0.12	...	...
KOI-2754		2013 Aug 14	LP600	21	0.79 ± 0.06	260 ± 3	2.23 ± 0.20	D14, K16	...
KOI-2771		2013 Aug 16	LP600	13	3.85 ± 0.06	312 ± 2	6.61 ± 0.14	D14	...
KOI-2803	12.1	2013 Aug 13	LP600	25	3.84 ± 0.06	61 ± 2	3.00 ± 0.05	D14, K16	...
KOI-2807	13.7	2013 Jul 28	LP600	13	3.93 ± 0.06	77 ± 2	1.90 ± 0.04	...	...
KOI-2812	14.2	2013 Jul 27	LP600	22	2.09 ± 0.06	335 ± 2	3.23 ± 0.05	...	...
KOI-2836	14.9	2013 Oct 22	LP600	217	3.94 ± 0.06	70 ± 2	3.39 ± 0.04	...	...
KOI-2837	13.1	2013 Aug 15	LP600	6	0.35 ± 0.06	136 ± 5	0.23 ± 0.04	...	yes
KOI-2848	12.3	2013 Aug 14	LP600	6	2.30 ± 0.06	28 ± 2	5.63 ± 0.23	...	...
KOI-2904	12.5	2013 Jul 24	LP600	10	0.71 ± 0.06	226 ± 3	1.99 ± 0.24	D14	yes
KOI-2910	15.0	2013 Aug 19	LP600	7	3.15 ± 0.06	88 ± 2	0.72 ± 0.05	...	...
KOI-2962	14.0	2013 Jul 25	LP600	9	1.13 ± 0.06	68 ± 2	0.53 ± 0.05	...	...
KOI-3069	14.7	2013 Aug 19	LP600	5	1.93 ± 0.06	109 ± 2	2.20 ± 0.07	...	yes
KOI-3073	14.2	2013 Aug 14	LP600	10	1.30 ± 0.06	10 ± 2	1.76 ± 0.15	...	...
KOI-3158		2013 Jul 21	LP600	613	2.10 ± 0.06	254 ± 2	4.00 ± 0.15	LB14, K16, C15	...
KOI-3190	11.1	2013 Jul 27	LP600	6	2.68 ± 0.06	190 ± 2	5.92 ± 0.17	...	...
KOI-3245	12.3	2013 Jul 25	LP600	12	1.58 ± 0.06	184 ± 2	3.10 ± 0.07	...	...
KOI-3324	15.7	2013 Oct 23	LP600	11	3.84 ± 0.06	323 ± 2	3.05 ± 0.06	...	...
KOI-3339	14.4	2013 Oct 22	LP600	9	3.41 ± 0.06	346 ± 2	1.38 ± 0.06	...	...

Table 2
(Continued)

KOI	m_i (mag)	ObsID	Filter	Signf. σ	Separation (arcsec)	P.A. (deg.)	Mag. Diff. (mag)	Previous Detection?	NIRC2 Detection?
KOI-3468	14.1	2013 Jul 24	LP600	6	1.49 ± 0.06	117 ± 2	3.22 ± 0.15	...	...
KOI-3497	13.0	2013 Oct 24	LP600	15	0.78 ± 0.06	174 ± 3	1.23 ± 0.12	M14, K16	...
KOI-3891	13.4	2013 Jul 27	LP600	5	1.05 ± 0.06	240 ± 2	4.69 ± 0.41	K16	...
				9	2.01 ± 0.06	136 ± 2	4.92 ± 0.13	K16	...
KOI-3907	12.5	2013 Jul 27	LP600	7	1.58 ± 0.06	162 ± 2	6.31 ± 0.25	W15	...
				20	2.82 ± 0.06	72 ± 2	3.23 ± 0.04	W15	...
KOI-4004	12.5	2013 Jul 27	LP600	13	1.93 ± 0.06	217 ± 2	4.34 ± 0.27	K16	yes
KOI-4021	12.5	2013 Aug 16	LP600	11	1.92 ± 0.06	113 ± 2	0.52 ± 0.07	...	...
KOI-4145	14.1	2013 Jul 27	LP600	9	2.71 ± 0.06	237 ± 2	2.36 ± 0.03	...	...
KOI-4149	14.1	2013 Oct 22	LP600	11	1.76 ± 0.06	63 ± 2	0.17 ± 0.03	...	...
KOI-4205	14.2	2013 Jul 28	LP600	7	2.71 ± 0.06	66 ± 2	2.65 ± 0.03	...	...
KOI-4209	15.7	2013 Aug 19	LP600	11	0.96 ± 0.06	203 ± 2	0.37 ± 0.08	...	yes
KOI-4287	11.1	2013 Aug 17	LP600	10	0.61 ± 0.06	76 ± 3	1.27 ± 0.14	K16	...
KOI-4329	11.9	2013 Aug 18	LP600	10	1.93 ± 0.06	117 ± 2	4.64 ± 0.21	...	...
KOI-4331	13.0	2013 Jul 29	LP600	6	0.45 ± 0.06	103 ± 4	0.25 ± 0.04	...	yes
KOI-4389	14.8	2013 Aug 21	LP600	7	2.88 ± 0.06	332 ± 2	0.58 ± 0.06	...	...
KOI-4399	11.8	2013 Jul 24	LP600	6	2.16 ± 0.06	17 ± 2	6.24 ± 0.21	K16	...
KOI-4407	11.0	2013 Jul 24	LP600	19	2.54 ± 0.06	298 ± 2	2.97 ± 0.05	E15, K16	yes
KOI-4463	14.6	2013 Jul 27	LP600	29	2.45 ± 0.06	143 ± 2	0.01 ± 0.03	...	yes
KOI-4495	15.2	2013 Aug 22	LP600	6	3.06 ± 0.06	89 ± 2	3.90 ± 0.06	...	...
				9	3.41 ± 0.06	344 ± 2	2.68 ± 0.05	...	...
KOI-4567	13.6	2013 Jul 24	LP600	12	1.31 ± 0.06	142 ± 2	2.48 ± 0.13	...	...
KOI-4575	13.0	2013 Aug 16	LP600	18	2.97 ± 0.06	61 ± 2	2.18 ± 0.03	...	...
KOI-4580	12.8	2013 Aug 13	LP600	19	1.58 ± 0.06	60 ± 2	1.27 ± 0.05	...	...
KOI-4582	11.6	2013 Jul 27	LP600	68	2.71 ± 0.06	308 ± 2	6.28 ± 0.18	K16	...
				39	3.55 ± 0.06	286 ± 2	3.27 ± 0.12	K16	...
KOI-4634	13.5	2013 Jul 24	LP600	5	0.35 ± 0.06	275 ± 5	1.55 ± 0.18	...	yes
KOI-4651	13.6	2013 Jul 25	LP600	9	1.22 ± 0.06	105 ± 2	2.88 ± 0.37	...	...
KOI-4656	13.7	2013 Jul 29	LP600	8	2.89 ± 0.06	23 ± 2	1.42 ± 0.03	...	...
KOI-4657	13.0	2013 Jul 29	LP600	22	2.11 ± 0.06	234 ± 2	3.27 ± 0.10	K16	...
KOI-4792	14.0	2013 Aug 15	LP600	9	3.68 ± 0.06	318 ± 2	2.36 ± 0.04	...	...
KOI-4797	15.3	2013 Aug 22	LP600	6	3.59 ± 0.06	127 ± 2	1.12 ± 0.06	...	...
KOI-4813	13.3	2013 Jul 28	LP600	5	2.54 ± 0.06	208 ± 2	1.22 ± 0.05	...	...
KOI-4823	12.5	2013 Aug 17	LP600	16	1.40 ± 0.06	153 ± 2	0.59 ± 0.04	...	...
KOI-4871	12.9	2013 Oct 25	LP600	11	0.96 ± 0.06	333 ± 2	3.12 ± 0.19	^a	yes

Notes. References for previous detections are denoted with the following codes: Adams et al. 2012 (A12), Campante et al. 2015 (C15), Dressing et al. 2014 (D14), Everett et al. 2015 (E15), Gaidos et al. 2016 (G16), Howell et al. 2011 (H11), Horch et al. 2012 (H12), Kraus et al. 2016 (K16), Lillo-Box et al. 2012 (LB12), Lillo-Box et al. 2014 (LB14), Muirhead et al. 2014 (M14), Teske et al. 2015 (Te15), Wang et al. 2015b (W15).

^a Companion identity is ambiguous. See Section 5.2.

evidence to the spectroscopic companions existing at closer angular separations.

We detected a companion to KOI-151 at an angular separation of $4''.2$ and at a radiant flux ratio of 0.0046 ± 0.0008 with respect to the primary star. This companion is fainter than the 1σ lower limit on the radiant flux of 0.012 ± 0.006 determined by Kolbl et al. (2015) and was likely not captured by the HIRES entrance slit. Therefore, we conclude that our detection is new and that KOI-151 is an asterism of at least three stars.

We detected a companion to KOI-652 at an angular separation of $1''.23$. This companion was also detected by Teske et al. (2015) and Kraus et al. (2016) with Keck-NIRC2 as a $\sim 0''.08$ binary. This lends further evidence to Kolbl et al.'s claim that this system is at least a triple star system.

Both we and Wang et al. (2015b) detected a companion to KOI-1784 at an angular separation of $\sim 0''.3$, which would easily be captured within the HIRES entrance slit. We calculate a radiant flux ratio of 0.59 ± 0.07 , which is well above the lower limit of 0.192 ± 0.058 determined by Kolbl et al. (2015).

Wang et al. (2015b) estimated a physical separation of 160.7 AU between the primary and the companion, and this may not be compatible with the ΔRV of -13 km s^{-1} measured by Kolbl et al. (2015). It is not conclusive that the imaged close companion is also responsible for the spectroscopic signal, so it is possible this is also an asterism of at least three stars.

We observed a companion to KOI-4871 at an angular separation of $0''.96$ and a radiant flux ratio of 0.057 ± 0.010 with respect to the primary star. This detection is compatible with the lower limit on the radiant flux ratio of 0.012 ± 0.003 determined by Kolbl et al. (2015). If this is indeed the same star, Kolbl et al.'s reported ΔRV of -23 km s^{-1} suggests it is not physically associated with the primary.

While we have not conclusively imaged stellar companions that were detected by Kolbl et al.'s survey, we have found additional nearby stars not detected by spectroscopic methods. As previously suggested by Teske et al. (2015), spectroscopic and AO methods can probe complementary, and sometimes overlapping, regions of parameter space when searching for stellar companions. While spectroscopic companions can be

Table 3
Detections of Objects Within $\sim 4''$ of *Kepler* Planet Candidates at $< 5\sigma$ Significance

KOI	m_i (mag)	ObsID	Filter	Signf. σ	Separation (arcsec)	P.A. (deg.)	Mag. Diff. (mag)	Previous Detection?	NIRC2 Detection?
KOI-151	13.8	2013 Jul 27	LP600	4.2	4.17 ± 0.06	58 ± 2	5.84 ± 0.18	...	...
KOI-155	13.3	2013 Aug 13	LP600	4.0	4.01 ± 0.06	251 ± 2	3.83 ± 0.17	...	...
KOI-190	13.9	2013 Jul 27	LP600	3.6	0.23 ± 0.06	105 ± 2	1.33 ± 0.18	...	yes
KOI-251	14.1	2013 Aug 21	LP600	2.1	3.48 ± 0.06	123 ± 2	3.80 ± 0.12	A12, G16, K16	...
KOI-285		2013 Aug 13	LP600	4.6	1.51 ± 0.06	136 ± 2	6.12 ± 0.21	A12, K16	...
KOI-387	13.2	2013 Jul 29	LP600	2.3	0.98 ± 0.06	352 ± 2	3.86 ± 0.18	LB12, K16	...
KOI-425	14.5	2013 Aug 22	LP600	2.8	0.53 ± 0.06	346 ± 4	0.86 ± 0.10	...	yes
KOI-438	13.8	2013 Aug 18	LP600	3.9	3.28 ± 0.06	181 ± 2	3.11 ± 0.04	K16	...
KOI-507	14.6	2013 Aug 22	LP600	2.3	2.03 ± 0.06	358 ± 2	4.46 ± 0.11	...	...
KOI-584	13.9	2012 Aug 05	LP600	2.5	1.83 ± 0.06	137 ± 2	4.10 ± 0.12	...	...
KOI-592	14.1	2013 Aug 14	LP600	2.6	2.30 ± 0.06	150 ± 2	4.21 ± 0.11	LB12	...
KOI-614	14.3	2013 Jul 29	LP600	2.2	2.76 ± 0.06	214 ± 2	4.01 ± 0.03	...	...
KOI-730	15.1	2013 Aug 21	LP600	3.8	2.04 ± 0.06	237 ± 2	2.95 ± 0.09	...	...
KOI-813	15.5	2013 Aug 22	LP600	4.3	3.87 ± 0.06	137 ± 2	2.09 ± 0.08	...	...
KOI-931	15.0	2013 Oct 23	LP600	4.0	1.38 ± 0.06	177 ± 2	3.40 ± 0.14	...	yes
KOI-999	15.0	2013 Aug 18	LP600	2.6	3.41 ± 0.06	125 ± 2	2.80 ± 0.05	...	...
KOI-1066	15.4	2013 Aug 21	LP600	2.2	1.69 ± 0.06	205 ± 2	4.19 ± 0.18	...	yes
KOI-1067	14.5	2013 Oct 23	LP600	3.5	2.97 ± 0.06	143 ± 2	4.05 ± 0.15	...	yes
KOI-1112	14.4	2013 Jul 27	LP600	2.5	2.95 ± 0.06	172 ± 2	4.57 ± 0.05	...	yes
KOI-1214	14.4	2013 Jul 24	LP600	3.9	0.33 ± 0.06	132 ± 2	1.21 ± 0.18	...	yes
KOI-1397	14.8	2013 Aug 21	LP600	3.1	2.30 ± 0.06	229 ± 2	4.41 ± 0.17	K16	...
KOI-1495	15.2	2013 Aug 22	LP600	2.5	3.75 ± 0.06	188 ± 2	2.92 ± 0.11	...	...
KOI-1546	14.2	2013 Aug 19	LP600	4.2	4.15 ± 0.06	165 ± 2	3.34 ± 0.07	LB14	yes
				3.5	2.93 ± 0.06	5 ± 2	3.52 ± 0.08	LB14	yes
KOI-1573	14.2	2013 Jul 25	LP600	3.7	3.84 ± 0.06	299 ± 2	4.72 ± 0.15	...	...
KOI-1599	14.6	2013 Aug 18	LP600	3.4	2.98 ± 0.06	207 ± 2	2.22 ± 0.06	...	...
				2.6	3.42 ± 0.06	316 ± 2	2.89 ± 0.05	...	...
KOI-1700	14.1	2013 Jul 27	LP600	3.6	0.29 ± 0.06	289 ± 2	1.07 ± 0.26	...	yes
KOI-1784	13.4	2013 Jul 28	LP600	4.7	0.33 ± 0.06	286 ± 6	0.58 ± 0.13	K15, W15	yes
KOI-1798	14.2	2013 Aug 13	LP600	2.4	3.81 ± 0.06	186 ± 2	3.75 ± 0.21	...	...
KOI-1830	14.2	2013 Jul 27	LP600	3.9	0.46 ± 0.06	319 ± 4	1.29 ± 0.17	...	...
KOI-1950	15.7	2013 Aug 22	LP600	3.6	3.35 ± 0.06	326 ± 2	1.69 ± 0.05	...	...
KOI-1985	13.4	2013 Jul 24	LP600	2.2	2.82 ± 0.06	156 ± 2	4.19 ± 0.09	K16	...
KOI-1989	13.1	2013 Aug 14	LP600	2.9	1.12 ± 0.06	41 ± 2	3.49 ± 0.16	...	yes
KOI-2014	15.4	2013 Oct 23	LP600	3.1	3.75 ± 0.06	267 ± 2	2.50 ± 0.04	...	...
KOI-2019	15.4	2013 Aug 22	LP600	3.3	4.01 ± 0.06	105 ± 2	2.61 ± 0.21	...	...
KOI-2055	14.3	2013 Jul 25	LP600	2.2	3.80 ± 0.06	57 ± 2	4.09 ± 0.05	...	...
KOI-2056	14.3	2013 Aug 16	LP600	4.9	3.87 ± 0.06	131 ± 2	3.37 ± 0.11	...	...
KOI-2069	13.6	2013 Aug 14	LP600	2.7	1.12 ± 0.06	108 ± 2	4.24 ± 0.51	...	...
KOI-2083	13.4	2013 Jul 28	LP600	2.5	0.26 ± 0.06	176 ± 2	1.03 ± 0.18	...	yes
KOI-2115	15.8	2013 Jul 21	LP600	2.4	3.59 ± 0.06	243 ± 2	2.75 ± 0.12	...	...
KOI-2156	15.3	2013 Aug 18	LP600	2.0	3.35 ± 0.06	303 ± 2	2.64 ± 0.05	G16, K16	...
KOI-2247	14.0	2013 Jul 27	LP600	2.3	1.90 ± 0.06	355 ± 2	5.12 ± 0.21	...	...
KOI-2314	14.4	2013 Jul 27	LP600	4.6	4.14 ± 0.06	201 ± 2	3.45 ± 0.22	...	...
KOI-2317	14.1	2013 Jul 27	LP600	4.6	1.51 ± 0.06	110 ± 2	4.93 ± 0.19	...	yes
KOI-2377	14.5	2013 Jul 24	LP600	4.3	4.11 ± 0.06	326 ± 2	4.04 ± 0.12	...	yes
KOI-2380	14.0	2013 Jul 24	LP600	4.0	4.01 ± 0.06	250 ± 2	2.46 ± 0.08	...	...
KOI-2421	14.0	2013 Jul 25	LP600	4.1	4.07 ± 0.06	132 ± 2	3.87 ± 0.18	D14	...
KOI-2469	14.7	2013 Aug 18	LP600	3.8	4.18 ± 0.06	114 ± 2	2.44 ± 0.17	...	...
KOI-2493	15.0	2013 Aug 22	LP600	2.4	2.69 ± 0.06	300 ± 2	2.68 ± 0.04	...	...
KOI-2516	13.1	2013 Jul 27	LP600	4.0	3.42 ± 0.06	84 ± 2	5.93 ± 0.04	D14	...
KOI-2542	14.8	2013 Aug 21	LP600	3.4	0.88 ± 0.06	22 ± 3	1.20 ± 0.19	G16, K16	yes
KOI-2551	15.5	2013 Oct 23	LP600	3.5	2.69 ± 0.06	197 ± 2	1.93 ± 0.03	...	...
KOI-2601	13.8	2013 Aug 13	LP600	3.8	1.44 ± 0.06	297 ± 2	3.61 ± 0.14	...	...
KOI-2664	15.3	2013 Aug 18	LP600	4.4	1.17 ± 0.06	90 ± 2	0.83 ± 0.09	...	yes
KOI-2681	15.7	2013 Oct 23	LP600	4.2	1.10 ± 0.06	161 ± 2	1.25 ± 0.11	...	yes
KOI-2707	14.2	2013 Jul 24	LP600	2.2	3.28 ± 0.06	217 ± 2	4.71 ± 0.16	...	...
				2.9	3.87 ± 0.06	182 ± 2	3.64 ± 0.11	...	...
KOI-2722	13.1	2013 Aug 14	LP600	3.7	3.27 ± 0.06	282 ± 2	5.88 ± 0.14	D14	yes
KOI-2743	13.5	2013 Aug 14	LP600	3.1	2.36 ± 0.06	182 ± 2	3.79 ± 0.08	...	...
KOI-2779	14.8	2013 Oct 22	LP600	2.9	0.98 ± 0.06	61 ± 2	2.54 ± 0.38	...	...
KOI-2838	13.2	2013 Aug 13	LP600	2.4	1.74 ± 0.06	197 ± 2	5.92 ± 0.35	D14	...
KOI-2859	13.6	2013 Aug 16	LP600	3.1	0.47 ± 0.06	282 ± 5	2.12 ± 0.23	...	yes

Table 3
(Continued)

KOI	m_i (mag)	ObsID	Filter	Signf. σ	Separation (arcsec)	P.A. (deg.)	Mag. Diff. (mag)	Previous Detection?	NIRC2 Detection?
KOI-2914	12.1	2013 Jul 24	LP600	2.4	3.80 ± 0.06	231 ± 2	5.64 ± 0.06	D14	...
KOI-2949	13.1	2013 Jul 29	LP600	2.2	2.36 ± 0.06	311 ± 2	4.08 ± 0.32	...	...
KOI-2971	12.6	2013 Jul 24	LP600	3.9	0.53 ± 0.06	209 ± 4	1.33 ± 0.18	...	yes
KOI-2984	12.9	2013 Jul 24	LP600	4.1	3.47 ± 0.06	33 ± 2	4.34 ± 0.05	D14	...
KOI-3029	14.7	2013 Aug 18	LP600	3.1	0.28 ± 0.06	272 ± 2	0.68 ± 0.22	...	yes
KOI-3041	14.0	2013 Jul 25	LP600	3.2	2.03 ± 0.06	128 ± 2	4.64 ± 0.17	...	...
KOI-3255	13.9	2013 Jul 27	LP600	2.2	3.15 ± 0.06	44 ± 2	4.87 ± 0.05	E15, K16	...
KOI-3277	12.9	2013 Jul 24	LP600	2.1	2.45 ± 0.06	355 ± 2	5.79 ± 0.23	...	...
				3.8	3.41 ± 0.06	353 ± 2	5.00 ± 0.12	...	...
KOI-3284	13.8	2013 Aug 22	LP600	4.2	3.94 ± 0.06	4 ± 2	2.42 ± 0.08	To15, E15, G16, K16	...
KOI-3288	14.0	2013 Jul 24	LP600	2.4	3.17 ± 0.06	75 ± 2	4.32 ± 0.12	...	...
				2.1	3.50 ± 0.06	80 ± 2	4.62 ± 0.16	...	...
KOI-3309	14.4	2013 Aug 17	LP600	3.2	3.71 ± 0.06	42 ± 2	2.78 ± 0.04	K16	...
KOI-3377	14.9	2013 Aug 22	LP600	2.7	1.45 ± 0.06	58 ± 2	4.26 ± 0.19	...	yes
KOI-3401	14.2	2013 Jul 28	LP600	4.3	0.65 ± 0.06	94 ± 3	0.89 ± 0.20	...	...
KOI-3439	14.0	2013 Jul 24	LP600	2.8	3.42 ± 0.06	228 ± 2	3.97 ± 0.05	...	...
KOI-3444	13.0	2013 Jul 25	LP600	2.6	1.11 ± 0.06	8 ± 2	3.32 ± 0.17	LB14, W15, G16, K16	...
				3.2	3.55 ± 0.06	262 ± 2	3.41 ± 0.23	LB14, W15, G16, K16	...
KOI-3459	15.0	2013 Aug 21	LP600	3.3	3.35 ± 0.06	124 ± 2	2.37 ± 0.04	...	...
KOI-3460	14.3	2013 Jul 27	LP600	2.5	1.24 ± 0.06	153 ± 2	5.08 ± 0.13	...	...
				2.8	2.47 ± 0.06	231 ± 2	5.52 ± 0.11	...	...
KOI-3486	14.1	2013 Jul 24	LP600	2.7	4.16 ± 0.06	260 ± 2	4.06 ± 0.12	...	...
KOI-3500	13.0	2013 Jul 25	LP600	4.1	2.54 ± 0.06	137 ± 2	4.01 ± 0.05	...	...
KOI-3946	13.1	2013 Aug 13	LP600	3.9	4.27 ± 0.06	61 ± 2	5.26 ± 0.13	...	...
KOI-4053	12.6	2013 Jul 25	LP600	3.2	4.11 ± 0.06	302 ± 2	5.51 ± 0.12	...	...
KOI-4098	13.5	2013 Aug 15	LP600	4.5	0.78 ± 0.06	174 ± 3	1.10 ± 0.22	...	...
KOI-4166	15.0	2013 Aug 18	LP600	2.0	3.54 ± 0.06	157 ± 2	3.29 ± 0.04	...	...
KOI-4194	15.0	2013 Aug 21	LP600	2.3	2.17 ± 0.06	290 ± 2	3.41 ± 0.07	...	...
KOI-4208	15.3	2013 Aug 17	LP600	3.3	0.99 ± 0.06	234 ± 2	2.57 ± 0.29	...	...
KOI-4226	12.6	2013 Jul 24	LP600	4.7	2.49 ± 0.06	267 ± 2	4.18 ± 0.03	K16	...
KOI-4274	15.1	2013 Aug 22	LP600	3.1	3.26 ± 0.06	207 ± 2	3.71 ± 0.11	...	...
				2.4	4.54 ± 0.06	327 ± 2	4.11 ± 0.13	...	...
KOI-4313	14.1	2013 Aug 13	LP600	2.6	2.88 ± 0.06	81 ± 2	4.19 ± 0.05	...	...
KOI-4409	12.3	2013 Jul 24	LP600	2.3	2.89 ± 0.06	139 ± 2	6.10 ± 0.10	...	...
KOI-4443	13.7	2013 Aug 13	LP600	2.2	3.41 ± 0.06	26 ± 2	5.00 ± 0.13	...	...
KOI-4495	15.2	2013 Aug 22	LP600	3.9	3.04 ± 0.06	58 ± 2	4.73 ± 0.09	...	...
KOI-4523	14.6	2013 Aug 21	LP600	2.4	3.94 ± 0.06	100 ± 2	2.61 ± 0.33	...	...
KOI-4699	12.8	2013 Aug 13	LP600	2.8	4.01 ± 0.06	285 ± 2	5.93 ± 0.21	...	...
KOI-4768	15.4	2013 Oct 23	LP600	2.3	1.30 ± 0.06	159 ± 2	3.99 ± 0.26	...	yes
KOI-4797	15.3	2013 Aug 22	LP600	3.5	3.93 ± 0.06	77 ± 2	3.37 ± 0.11	...	...
KOI-4812	15.5	2013 Oct 23	LP600	3.6	3.15 ± 0.06	100 ± 2	1.84 ± 0.03	...	...
KOI-4813	13.3	2013 Jul 28	LP600	4.6	4.03 ± 0.06	146 ± 2	3.34 ± 0.09	...	...

Note. References for previous detections are denoted with the following codes: Adams et al. 2012 (A12), Dressing et al. 2014 (D14), Everett et al. 2015 (E15), Gaidos et al. 2016 (G16), Kolbl et al. 2015 (K15), Kraus et al. 2016 (K16), Lillo-Box et al. 2012 (LB12), Lillo-Box et al. 2014 (LB14), Torres et al. 2015 (To15), Wang et al. 2015b (W15).

detected at much closer angular separations, AO observations probe larger angular separations, and at a much greater dynamic range that can be used to more precisely calibrate transit radii measurements. Physical association of companions can be established either from the difference in measured radial velocities from spectroscopy or from probabilistic or additional spectrophotometric parallax analysis when using AO. From a practical perspective, AO imaging requires much less on-sky observing time, and can target a much greater range of exoplanetary host stars.

5.3. Keck-NIRC2 Imaging of Robo-AO Observed KOIs

Details of the 50 observations and 63 companions detected with NIRC2 appear in Table 4. We observed 14 KOIs with

companions detected at $>5\sigma$ so we could later calculate spectrophotometric parallax distances to determine the probability of physical association. We observed 13 companions detected by Paper I at a significance level of $<5\sigma$. Including those previously imaged with NIRC2 and by Lillo-Box et al. (2012) and Adams et al. (2012), all 17 of these detections have been confirmed.

The remainder of KOIs we observed with NIRC2 were at various levels of analysis: some Robo-AO images had been fully processed with measured significance levels on the candidate companion, while others were manually identified before PSF subtraction. We confirmed 24 of the companions detected at a significance level of $<5\sigma$ in this survey (2 of which were in systems with a $>5\sigma$ detected companion), and

Table 4
Full Keck-NIRC2 Observation List and Detected Companions

KOI	ObsID	Filter	Separation (arcsec)	P.A. (deg.)	Mag. Diff. (mag)	Notes
KOI-190	2015 Jul 25	Kp	0.180 ± 0.010	109 ± 3	0.64 ± 0.14	Table 3
KOI-425	2015 Jul 25	Kp	0.490 ± 0.010	343 ± 1	0.83 ± 0.06	Table 3
KOI-628	2013 Aug 25	Kp	1.828 ± 0.005	311 ± 1	3.87 ± 0.06	^c
			2.752 ± 0.005	239 ± 1	3.00 ± 0.06	^a
KOI-931	2015 Jul 25	Kp	1.261 ± 0.005	177 ± 1	3.23 ± 0.06	Table 3
KOI-987	2013 Aug 25	Kp	1.977 ± 0.005	226 ± 1	2.24 ± 0.06	^c
KOI-1066	2014 Aug 17	Kp	1.687 ± 0.005	231 ± 1	2.95 ± 0.07	Table 3
KOI-1067	2014 Aug 17	Kp	2.923 ± 0.005	142 ± 1	3.79 ± 0.11	Table 3
KOI-1112	2013 Aug 24	Kp	3.063 ± 0.005	172 ± 1	2.76 ± 0.07	Table 3
KOI-1151	2014 Aug 17	Kp	0.756 ± 0.010	307 ± 1	2.41 ± 0.06	^c
KOI-1214	2014 Aug 17	Kp	0.347 ± 0.010	136 ± 2	2.46 ± 0.06	Table 3
KOI-1359	2013 Jun 25	Ks	1.387 ± 0.005	332 ± 1	2.17 ± 0.06	^c
KOI-1375	2014 Aug 17	Kp	0.785 ± 0.010	27 ± 1	3.39 ± 0.07	^c
KOI-1442	2013 Aug 25	Kp	2.113 ± 0.005	71 ± 1	3.63 ± 0.06	^c
KOI-1546	2013 Aug 24	Kp	0.600 ± 0.010	90 ± 1	0.73 ± 0.05	Table 2
			2.918 ± 0.005	4 ± 1	2.95 ± 0.08	Table 3
			4.108 ± 0.005	165 ± 1	3.48 ± 0.06	Table 3
KOI-1700	2014 Aug 17	Kp	0.274 ± 0.010	288 ± 2	0.55 ± 0.06	Table 3
KOI-1784	2015 Jul 25	Kp	0.279 ± 0.010	291 ± 2	0.78 ± 0.06	Table 3
KOI-1845	2013 Jun 25	Ks	1.996 ± 0.005	79 ± 1	2.89 ± 0.06	^c
			2.963 ± 0.005	348 ± 1	4.40 ± 0.09	^a
KOI-1884	2013 Aug 24	K	0.934 ± 0.010	95 ± 1	2.31 ± 0.06	^c
			1.838 ± 0.005	82 ± 1	2.73 ± 0.06	^b
			2.567 ± 0.005	327 ± 1	3.20 ± 0.14	^b
KOI-1891	2013 Aug 24	Kp	2.069 ± 0.005	211 ± 1	4.60 ± 0.07	^c
KOI-1989	2015 Jul 25	Kp	0.817 ± 0.010	40 ± 1	2.92 ± 0.06	Table 3
KOI-2009	2013 Aug 25	Kp	1.511 ± 0.005	178 ± 1	2.75 ± 0.06	^c
KOI-2083	2014 Aug 17	Kp	0.252 ± 0.010	166 ± 1	1.60 ± 0.05	Table 3
KOI-2159	2014 Aug 17	Kp	2.018 ± 0.005	324 ± 1	2.48 ± 0.06	^c
KOI-2317	2015 Jul 25	Kp	1.512 ± 0.005	112 ± 1	3.92 ± 0.06	Table 3
KOI-2363	2014 Aug 17	Kp	1.952 ± 0.005	357 ± 1	5.04 ± 0.09	^b
KOI-2377	2013 Aug 24	Kp	2.186 ± 0.005	335 ± 1	0.63 ± 0.07	Table 2
			2.544 ± 0.005	42 ± 1	3.75 ± 0.12	^b
			3.911 ± 0.005	316 ± 1	3.55 ± 0.17	Table 3
KOI-2413	2013 Aug 25	Kp	0.308 ± 0.010	250 ± 2	0.17 ± 0.06	
KOI-2443	2013 Jun 25	Ks	1.383 ± 0.005	164 ± 1	3.63 ± 0.06	^c
KOI-2542	2015 Jul 25	Kp	0.765 ± 0.010	29 ± 1	0.60 ± 0.05	Table 3
KOI-2664	2015 Jul 25	Kp	1.180 ± 0.005	90 ± 1	1.10 ± 0.06	Table 3
KOI-2681	2014 Aug 17	Kp	1.132 ± 0.005	148 ± 1	0.43 ± 0.06	Table 3
KOI-2705	2013 Aug 24	Kp	1.900 ± 0.005	304 ± 1	2.58 ± 0.07	Table 2
KOI-2711	2014 Aug 17	Kp	0.466 ± 0.010	149 ± 1	0.12 ± 0.06	Table 2
KOI-2722	2014 Aug 17	Kp	3.226 ± 0.005	283 ± 1	3.77 ± 0.06	Table 3
KOI-2837	2013 Aug 24	Kp	0.347 ± 0.010	138 ± 2	0.20 ± 0.06	Table 2
KOI-2859	2014 Aug 17	Kp	0.454 ± 0.010	291 ± 1	2.89 ± 0.06	Table 3
KOI-2904	2013 Aug 24	Kp	0.700 ± 0.010	226 ± 1	2.45 ± 0.06	Table 2
KOI-2971	2015 Jul 25	Kp	0.301 ± 0.010	274 ± 2	3.57 ± 0.06	Table 3
			3.564 ± 0.005	38 ± 1	5.93 ± 0.17	^b
KOI-3029	2014 Aug 17	Kp	0.251 ± 0.010	264 ± 2	0.06 ± 0.06	Table 3
			1.734 ± 0.005	356 ± 1	4.49 ± 0.07	^b
			2.552 ± 0.005	4 ± 1	3.44 ± 0.07	^b
KOI-3069	2013 Aug 24	Kp	1.785 ± 0.005	108 ± 1	1.26 ± 0.06	Table 2
KOI-3377	2015 Jul 25	Kp	0.264 ± 0.010	335 ± 2	0.49 ± 0.06	^b
			1.405 ± 0.005	50 ± 1	3.74 ± 0.06	Table 3
KOI-4004	2015 Jul 25	Kp	1.958 ± 0.005	218 ± 1	2.37 ± 0.08	Table 2
KOI-4209	2013 Aug 24	Kp	0.975 ± 0.010	205 ± 1	0.57 ± 0.06	Table 2
KOI-4292	2013 Aug 25	Kp	1.951 ± 0.005	30 ± 1	4.54 ± 0.08	^b
KOI-4331	2014 Aug 17	Kp	0.347 ± 0.010	102 ± 2	0.13 ± 0.05	Table 2
KOI-4407	2013 Aug 25	Kp	2.455 ± 0.005	300 ± 1	1.89 ± 0.06	Table 2
			2.662 ± 0.005	311 ± 1	4.65 ± 0.34	^b
KOI-4463	2013 Aug 24	Kp	2.462 ± 0.005	144 ± 1	-0.26 ± 0.07	Table 2
KOI-4634	2015 Jul 25	Kp	0.282 ± 0.010	276 ± 2	0.65 ± 0.06	Table 2
KOI-4768	2014 Aug 17	Kp	1.326 ± 0.005	160 ± 1	2.61 ± 0.07	Table 3
KOI-4871	2014 Aug 17	Kp	0.921 ± 0.010	334 ± 1	3.04 ± 0.06	Table 2

Notes.^a Additional detection not reported in Paper I. (Angular separation exceeds $2''/5$.)^b Companion not detected in the Robo-AO image.^c Confirmation of $<5\sigma$ significance companions in Paper I.

Table 5
Full Robo-AO Observation List

KOI	m_i /mag	ObsID	Obs. Qual. ^a	Companion?
K00004.01	11.3	2012 Jul 16	high (i' -band)	yes
K00042.01	9.2	2013 Jul 28	high	yes
K00116.01	12.7	2013 Jul 24	high	...
K00123.01	12.2	2013 Jul 25	high	...
K00127.01	13.7	2013 Aug 15	high	...

Notes.

^a All observations taken in the LP600 filter unless otherwise noted by ' i' -band'

^b Companion originally discovered in NIRC2 image; see Table 4.

(This table is available in its entirety in machine-readable form.)

other surveys confirmed 18 more of these companions. Due to the enhanced contrast with NIRC2, we found additional companions to 6 KOIs (1884, 2377, 2971, 3029, 3377, and 4407) that were not detected in the original Robo-AO data. We also found individual companions near KOI-2363 and KOI-4292 in the NIRC2 data that did not correspond to the preliminary manually identified candidate companions in the Robo-AO data and we note them in Tables 4 and 5. Despite the somewhat haphazard selection of targets, the vast majority of Robo-AO detections that have follow-up observations with NIRC2 have been shown to be real; so far, 60 of the 120 companions detected at a significance of $<5\sigma$ with Robo-AO from Paper I and this work have been confirmed.

6. DISCUSSION

We observed 969 *Kepler* planetary system candidates with the Robo-AO robotic laser AO system. Presuming all confirmed and probable 203 Robo-AO detected companions within $\sim 4''$ of 181 KOIs are real, we calculate the nearby star probability as a function of angular distance; see Figure 7. In our previous study, we found a probability of $7.4\% \pm 1.0\%$ at angular separations up to $2''.5$ around 715 KOIs. For direct comparison, we calculated the probability in our sample to the same separation of $2''.5$ and found it to be $10.6\% \pm 1.1\%$, a difference of 2.2σ . Additional fainter companions are discovered here, e.g., 9 companions with a magnitude difference greater than 5 within $2''.5$ compared to 3 previously.

We explored the possibility of a bias change in the KOI selection process between major data releases, Q1-Q6 (Batalha et al. 2013) and Q1-Q12 (Rowe et al. 2015). Our first study comprised 715 targets solely from Q1-Q6, while this work includes targets originally identified in both catalogs, 505 that appear in Q1-Q6 (51 of which have $<2''.5$ companions) and 464 that only appear in Q1-Q12 (52 companions). After combining the results of both and comparing the nearby star probability within $2''.5$ for the KOIs that only appear in Q1-Q12 catalog versus those originally found in the Q1-Q6 catalog, we find probabilities of $11.2\% \pm 1.6\%$ and $8.5\% \pm 0.9\%$, respectively, a difference of 1.5σ .

We also examined the on-sky spatial distribution of observed KOIs and those with $<2''.5$ companions for both studies (Figure 6). In our cumulative survey there is a bias of targets located closer to the galactic plane compared to the center of the *Kepler* field. Additionally, compared to our first study, the median position of KOIs observed in this work is closer to the galactic plane by $1^\circ.1$, and the median position of KOIs with

$<2''.5$ companions is closer to the galactic plane by $1^\circ.4$. We find in general that higher galactic latitude KOIs have fewer wide companions which is consistent with lower stellar crowding away from the galactic plane in the *Kepler* field (Gilliland et al. 2011), and therefore the difference in nearby star probability between this work and Paper I may simply be due to the specific KOI samples.

Previous studies have shown that the majority of stellar companions to KOIs at a separation of $<1''$ are physically associated, with the probability of association decreasing with increasing angular separation (Horch et al. 2014). We calculate the cumulative nearby star probability as a function of angular separation of our data and present it in Figure 7. Our data show that the probability increases nearly linearly with increasing separation, up to $17.9\% \pm 1.4\%$ out to a separation of $4''.0$. If the distribution had consisted solely of chance alignments of non-physically associated companions, we would expect this probability to instead increase quadratically. This suggests again that a large fraction of the companions with smaller angular separations are indeed physically associated with the primary star.

This work and Paper I together comprise a survey of roughly half of the KOIs in the Q1-Q17 DR24 data set release. In light of the apparent discrepancy in companion discovery rates between the two using the same instrument, we caution against extrapolating companion rates from any individual survey that samples a small fraction of the overall population. Even when combined, the existing patchwork of other KOI surveys (see Section 5.1) is not as comprehensive, and requires detailed calibration to match the varying sensitivities, inner working angles, and wavelength ranges. Future high angular resolution follow-up observations of large numbers of candidate exoplanet hosts would benefit from an initial comprehensive survey from Robo-AO that can very efficiently find lower contrast blended stars; preserving precious and limited resources like Keck AO or *HST* for those targets that pass the initial round of vetting.

We expect that our data will be used by other researchers using *Kepler* data to study and validate exoplanets, their host stars, and stellar environments, and other astrophysical phenomena. To aid in this effort, Robo-AO images of KOIs and the position and photometry of any detected companions will be available at the *Kepler* Community Follow-up Observing Program.⁸

7. FUTURE WORK

In the third installment of this paper series we will present the remaining Robo-AO observations of KOIs and explore an analysis of the complete data set. We will detail the effects of the detected nearby stars on the interpretation of *Kepler* planetary candidates and note particular systems of interest. We will investigate further the spatial distribution of all KOIs with companions as a function of separation.

In parallel, we are currently using the multi-color visible and infrared observations obtained for this survey to estimate relative spectrophotometric distances between KOIs and their detected companions to determine if the stars are physically bound. We have also inspected all of our Robo-AO images of KOIs for images of other *Kepler* input catalog (KIC) targets that do not have repeating transit signals. We have identified

⁸ See <https://exofop.ipac.caltech.edu/cfop.php>.

Figure 6. Location in galactic coordinates for the KOIs (a), and those with companions detected at angular separations of less than $2''/5$ (b), observed by Paper I (PI) and in this work (PII). In both panels the “x” represents the median galactic coordinate for each set of objects. Projections of the *Kepler* detectors on sky for the spring season is provided for reference.

Figure 7. Cumulative companion fraction for Robo-AO observed KOIs as a function of angular separation. The dashed line represents a theoretical quadratic cumulative distribution that would be expected from non-physically associated companions.

nearly 700 of these serendipitously observed KICs in our existing data; we will use these observations as a control sample to determine if there is a fundamental difference in the nearby star probability between the KOIs and non-KOI KICs, including if there are similar effects due to galactic latitude, and whether this has an effect on planetary systems (Nofri et al. 2015).

We have reconfigured and redeployed the Robo-AO system as the only instrument on the 2.1 m telescope at Kitt Peak as of 2015 November (Riddle et al. 2016). We intend to continue observations of our detected companions to search for common proper motion pairs to better understand the probability of physical association. We will additionally integrate a science grade detector version of a low-noise infrared camera to Robo-AO (previously demonstrated by Baranec et al. 2015). This camera will enable both infrared imaging and tip-tilt sensing and correction that will allow us to better observe redder KOIs.

We are also in the process of building an upgraded Robo-AO system for the University of Hawai‘i 2.2 m telescope on Maunakea (Baranec et al. 2014b). Between the two Robo-AO systems, we will be able to observe up to ~ 500 objects per night, covering nearly three-quarters of the sky over the course of a year. Forthcoming transit missions such as NASA’s Transiting Exoplanet Survey Satellite (Ricker et al. 2015), scheduled to launch in 2017, and ESA’s PLANetary Transits and Oscillations of stars 2.0 (Rauer et al. 2014) will release their data on timescales of months and shorter, and are expected to discover a greater number of exoplanet systems compared to *Kepler*. Only the extremely efficient and rapid follow-up capability of Robo-AO will be able to keep up with the sustained demand for high-acuity imaging of thousands of exoplanet candidate host stars identified by these and other projects.

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Facilities: PO:1.5m (Robo-AO), Keck:II (NIRC2-LGS).

APPENDIX

In Table 5, we list our Robo-AO observed KOIs, including the date the target was observed, the observation quality as described in Section 3.5, and the presence of detected companions.

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