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A SEARCH FOR LOST PLANETS IN THE *KEPLER* MULTI-PLANET SYSTEMS AND THE DISCOVERY OF A LONG PERIOD, NEPTUNE-SIZED EXOPLANET KEPLER-150 F

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ABSTRACT

The vast majority of the 4700 confirmed planets and planet candidates discovered by the *Kepler* space telescope were first found by the *Kepler* pipeline. In the pipeline, after a transit signal is found, all data points associated with those transits are removed, creating a "Swiss cheese"-like light curve full of holes, which is then used for subsequent transit searches. These holes could render an additional planet undetectable (or "lost"). We examine a sample of 114 stars with 3+ confirmed planets to see the effect that this "Swiss cheesing" may have. A simulation determined that the probability that a transiting planet is lost due to the transit masking is low, but non-neglible, reaching a plateau at $\sim 3.3\%$ lost in the period range of $P = 400 - 500$ days. We then model the transits in all quarters of each star and subtract out the transit signals, restoring the in-transit data points, and use the Kepler pipeline to search the transit-subtracted (i.e., transit-cleaned) light curves. However, the pipeline did not discover any credible new transit signals. This demonstrates the validity and robustness of the *Kepler* pipeline's choice to use transit masking over transit subtraction. However, a follow-up visual search through all the transit-subtracted data, which allows for easier visual identification of new transits, revealed the existence of a new, Neptune-sized exoplanet. Kepler-150 f ($P = 637.2$ days, $R_{\rm P} = 3.86$ $R_\oplus$) is confirmed using a combination of false positive probability analysis, transit duration analysis, and the planet multiplicity argument.

Keywords: planetary systems — planets and satellites: detection

1. INTRODUCTION

The *Kepler* space telescope (Borucki et al. 2010) has discovered more than 4700 *Kepler* Objects of Interest (KOIs) that are classified either as confirmed planets ($\sim$ 2300, e.g., Rowe et al. 2014; Morton et al. 2016) or planet candidates ($\sim$ 2400, e.g., Coughlin et al. 2016), according to the NASA Exoplanet Archive (Akeson et al. 2013). The vast majority of these confirmed planets (CPs) and planet candidates (PCs) were initially discovered through the *Kepler* pipeline. One of the first steps of the pipeline is the Transit Planet Search (TPS) algorithm (Jenkins et al. 2010a). This searches the entire *Kepler* data set for potential transit signals, called Threshold Crossing Events (TCEs, Tenenbaum et al. 2012, 2013, 2014; Seader et al. 2015). Follow-up vetting for potential PC status is then performed, the latest version of which is described thoroughly in Section 3 of Coughlin et al. (2016). Additional vetting, such as follow-up observations, detailed light curve analysis, or statistical methods, can be used to confirm their planetary status or rule them out as false positives (FPs). Many of these KOIs are in systems with multiple KOIs, which allow for easier statistical validation of their planetary status (Lissauer et al. 2012). As such, about half of the CPs discovered with *Kepler* data are located in confirmed multiple planet systems.

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A detail in the TPS algorithm is its treatment of targets with multiple detections of TCEs. If a TCE is found for a target, TPS removes all the TCE's in-transit data points before TPS is rerun on the same light curve to search for more signals, creating what the *Kepler* team call a "Swiss cheese" light curve (Twicken et al. 2016). This masking of data points can hide the existence of additional planets whose transits overlap with the previously found TCEs.

An additional wrinkle arises when trying to discover long period planets in multiple planet systems. Large, long period planets with few transits are often best found by visually inspecting the light curves, especially for planets with < 3 transits, even more so if they only transit once (Wang et al. 2015; Uehara et al. 2016). In fact, a citizen science program called Planet Hunters (Fischer et al. 2012) that allows people online to visually search the *Kepler* data for exoplanets specializes in finding long period planets. Through the power of visual inspection, Planet Hunters has led to the discovery of three exoplanets (Schwamb et al. 2013; Wang et al. 2013; Schmitt et al. 2014b) and nearly 100 exoplanet candidates (Lintott et al. 2013; Wang et al. 2015; Schmitt et al. 2016). However, while these planets might be easy to spot visually, the fact that the light curve is filled with so many other planet transits can make them difficult to identify as new planets. They can be easily mistaken for or assumed to be a transit from another, known planet in the system. This problem could be fixed if the light curves had all known transit signals subtracted out, leaving only the previously undiscovered transits in the data.

In this paper, we examine a large fraction of the systems with three or more CPs and perform three separate analyses on them. First, we simulate the percentage of true planets missed by TPS because of the algorithm's removal of known in-transit data points. In our second test, we attempt to extract potential new planets in the data by subtracting out the transit signals of the known KOIs rather than masking out their transits altogether, after which we then rerun TPS on the new, transit-subtracted light curves. Lastly, we then examine the transit-subtracted light curves visually to search for evidence of additional planets.

2. SIMULATING FOR LOST PLANETS

Flattening light curves, re-fitting for planets, and then re-running TPS is a time intensive process. We also expect a higher rate of missed planets for systems with more known planets, as this corresponds to more data points being removed from subsequent transit searches. For these two reasons, we limited our study to only systems with three or more CPs, according to the NASA Exoplanet Archive (Akeson et al. 2013) as of January 6, 2016. Some of these systems, however, were removed from the analysis in later steps (see Section 3). The final sample includes 114 stars (see Table 2).

For each target star containing three or more CPs, we downloaded the long cadence data from the Barbara A. Mikulski Archive for Space Telescopes (MAST). In this sample of stars, the maximum time baseline was 1470 days. For each of the 114 stars in the sample, we then injected a planet into the light curve. The planet's period and the star's mass and radius were used to calculate the transit duration (assuming inclination $i = 0$), and a random epoch was chosen. The simulated planet's transits were counted as detectable if at least 50% of the transit was contained within the data (i.e., not in a data gap). The total number of transits detectable for each injection was then recorded. For this purpose, only the duration of the transit mattered, not the depth. We then repeated this for many periods and epochs, injecting 1000 planets into each one day period bin from 2 to 1472 days uniformly distributed in period and phase (e.g., 1000 planets with a period between 2 and 3 days, 1000 planets with a period between 3 and 4 days, etc.). A total of 169,050,000 planets were simulated.

This procedure was then repeated (with the same simulated planets) on the light curve after all in-transit data points from known KOIs were removed. Only those in-transit data points that we were able to successfully remove in our subsequent analysis (see Section 3) were removed in this step. Therefore, a small number of KOIs did not have their in-transit data points removed at this point.

The removal of the in-transit data points of the KOIs resulted in some of the transits that were originally detectable (pre-removal) becoming undetectable. This change in the window function (the Swiss cheesing of the light curve) generally would not be a problem when the planet transits the star many times. However, TPS requires three transits to register a detection, and the loss of one or more transits may bring a planet that had 3+ transits below that threshold. These planets are then no longer detectable. These are the "lost planets", the planets that would have been detected if in-transit data points were properly corrected for instead of removed.

There exists two shortcomings of this simulation. One is that, for planets with five or more transits, the removal of 2+ transits in a certain way could cause the subsequent planet detection to have an alias of the true period. For example, removing the second and fourth transit in a system with five consecutive transits results in a detected period double that of the true period. However, such events are rare, so its effects on the period detection are therefore ignored. Another complication is that this simulation did not test to see how the transit signal-to-noise was affected, only how the number of detectable transits was changed. Removing data points could reduce the signal-to-noise of undiscovered transits below the detection threshold. This implies that we are underestimating the number of lost planets caused by transit masking. See Section 6 for a more detailed discussion.

The probability of originally detectable planets becoming undetectable after the removal of the known in-transit data points is shown in Figure 1. The black line is the probability averaged over all stars, while the transparent gray lines in the background are the star-by-star probabilities, so that darker areas correspond to higher density regions. For the 114 stars in our sample, the lost planets are broadly distributed in period in a range of approximately 200-700 days. (A small number of planets are lost below $P = 200$ days, but this is almost exclusively for a small subset of stars that were observed for fewer quarters than the rest.) The distribution plateaus between 400 and 500 days with a peak in the 480-500 day period range. This 400-500 day peak has an average lost planet value of 3.3% level, meaning that 3.3% of the observable, transiting planets in this region would be expected to be undetected ("lost") after removing the in-transit points of previously found planets. In other words, if the planetary system had a planet in that period range, and if that planet transited, there would be a 3.3% chance that it would not have been detectable due solely to the Swiss cheesing of the light curve. The average's maximum of 4.6% occurs at $P = 493$ days. The star-by-star peaks, on the other hand, vary between 3.8-10.0%, with the peaks' locations ranging from $P = 135$ days to $P = 497$ days. These numbers, while small, are not negligible, and therefore imply that there may be a small number of missing exoplanets in the *Kepler* data caused by the removal of in-transit data points of known planets.

3. SEARCHING FOR LOST PLANETS

We began the analysis with the original Presearch Data Conditioning Simple Aperture Photometry (PDCSAP, Stumpe et al. 2012; Smith et al. 2012) fluxes for every *Kepler* star with 3+ CPs. We then removed the stellar variability using the PyKE

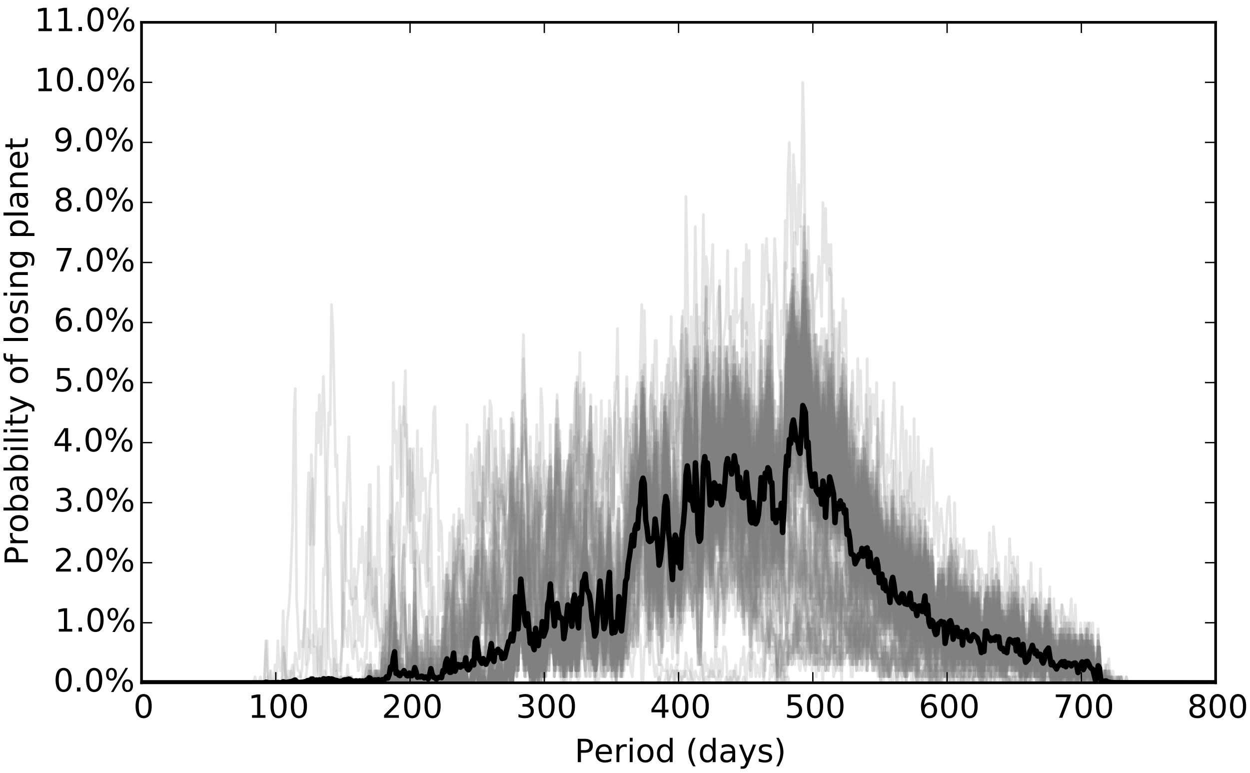

Figure 1. The probability of a planet that was originally detectable (i.e., had 3+ detectable transits) that became undetectable (i.e., had < 3 detectable transits) after the in-transit data points of the successfully fit KOIs were removed. A transit was ruled "detectable" if at least 50% of it was contained within the data (i.e., < 50% in a data gap). The probability of losing a planet at a certain period averaged over all stars is highlighted in black, while the star-by-star probabilities are shown in a transparent gray, so that darker areas correspond to higher density regions.

`kepflatten` command in PyRAF (Still & Barclay 2012). This command divides the light curve into chunks (or steps). The step size is usually on the order of one to a few days. It then fits the light curve in a window around (and including) the step with a polynomial (ignoring outliers). The window size is usually approximately double that of the step size so that the edge effects of fitting do not affect the center portion of the window. The window and step sizes were changed to fit each quarter of each star in order to remove as much of the stellar variability as possible without removing the transits. These detrended light curves were then stitched together into one FITS file. This was often successful as determined by eye (see Figure 2). However, a significant minority of stars had small, residual variability that could not be removed without disrupting the transit signal. Attempting to completely fit the stellar variability would cause the transits to become partially filled in because the in-transit data points would not register as outliers. The most egregious cases were those in which the frequency and magnitude of the stellar variability were greater than or approximately equal to the duration and depth of the planet, respectively. For these, the fitting procedure was unable to adequately fit the stellar variability without also removing the transit signal. The worst cases were removed from the analysis.

We then used the PyKE command `keptransit` (Still & Barclay 2012) to fit the KOIs in these systems across all observed quarters. For each star, this was done iteratively starting with the KOI with the largest depth. After this KOI was successfully fit, the KOI's transits were subtracted from the detrended light curve. Starting from this new, transit-subtracted and detrended light curve, we then performed the same procedure for the KOI with the next largest depth. This was repeated until all KOIs were fit and removed from the light curve. Initial parameter guesses for the fits were taken from the KOI cumuluative list, accessed 2016 Jan. 8, to get the most up-to-date (at the time) fit parameters. We chose to re-fit the transits rather than use the KOI list's values as fixed values to correct for any differences that our flattening made have induced in the transits. A sample of this fitting procedure's results is shown for Kepler-253 in Figures 2 and 3..

This fitting procedure was successful for the vast majority of cases, but not all. If a majority of a star's KOIs could not be successfully fit, it was removed from the analysis. Several examples of transit timing variations (TTVs) are also present in the data (Mazeh et al. 2013; Holczer et al. 2016). The `keptransit` command is not equipped to handle TTVs, so these were not properly fit. KOIs with TTVs from Mazeh et al. (2013) and Holczer et al. (2016) were noted, especially those which were visually apparent in the fitting results, in order to account for them in the later analysis. In the most egregious cases, such as Kepler-90 (Cabrera et al. 2014; Schmitt et al. 2014a), these TTVs were so large as to render the entire fit impossible or use-

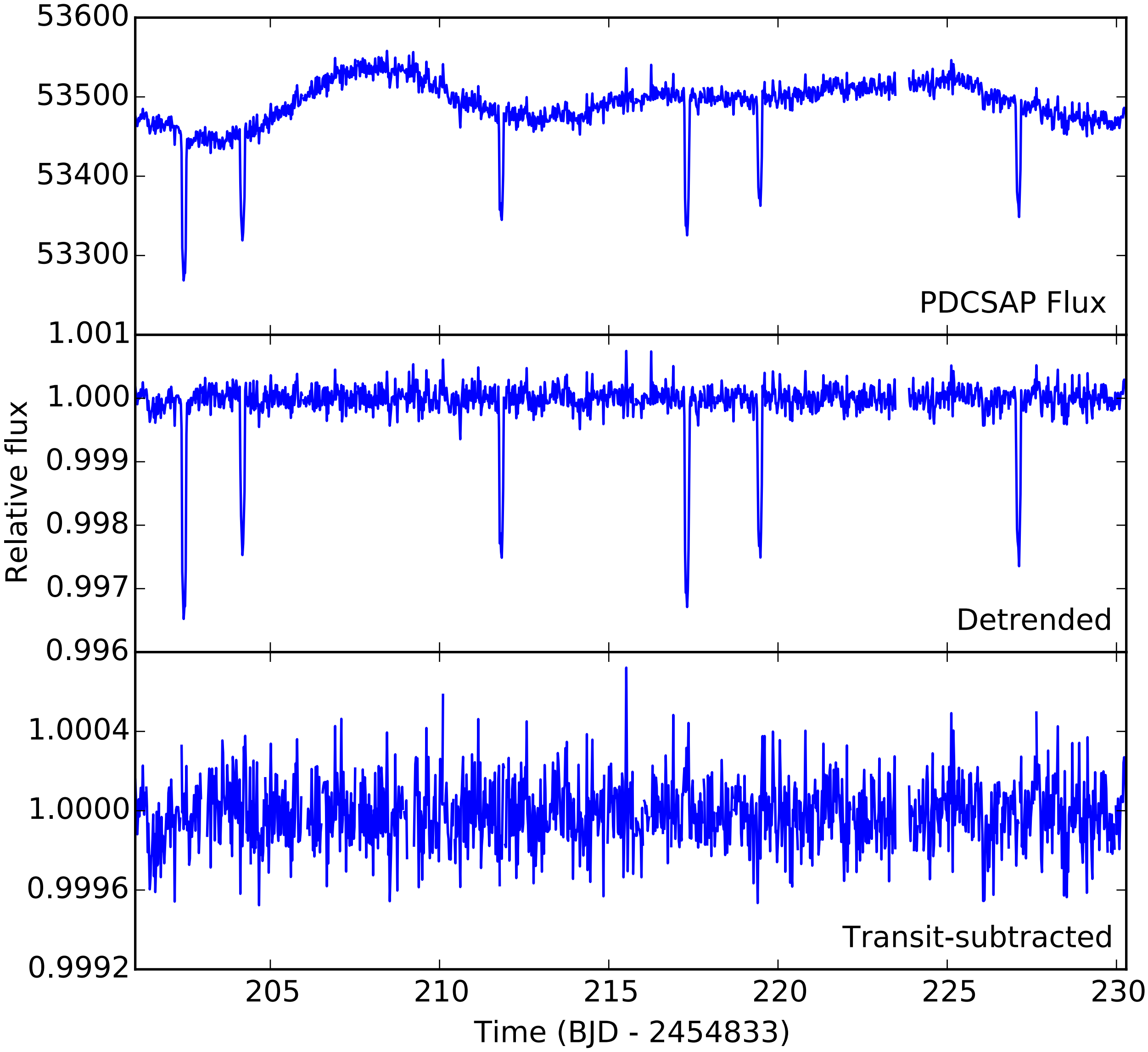

Figure 2. Thirty day portion of the light curve for Kepler-18 (KIC 8644288). *Top:* The PDCSAP flux, which was our starting point for the analysis. *Middle:* The PDCSAP flux detrended for variability. *Bottom:* The detrended flux after removing the transit signals from the KOIs in Kepler-18. Note that the y-scaling changes in each panel.

less. These TTV systems were removed.

The final count of systems that made it through all levels of analysis without being wholly removed is 114 stars, which host 397 CPs and 14 PCs. Of these, eight CPs and two PCs around nine stars were not successfully fit (see Table 2). These systems were still included in the analysis.

4. TRANSIT-SUBTRACTED SEARCH RESULTS

We then searched the detrended, transit-subtracted light curve of all 114 stars with TPS using [JON: HOW MANY CPU HOURS OR SOME OTHER UNIT] on the NASA Pleiades supercomputer. TPS found 33 new, unique signals in 24 stars that did not correspond to known KOIs. The new signals had between three and six transits. Each of these signals were cross-checked with the locations of the removed transits of known planets. There were 13 new signals that overlapped with at least one transit of a KOI that had been subtracted out. Two of them overlapped with two removed KOI transits, and four overlapped with three removed KOI transits. The other seven signals only overlapped with one removed KOI transit. The other 20 signals did not overlap at all with the removed KOI transits and thus could potentially have been found in earlier TPS searches. Regardless, we examined all 33 signals more closely.

For each signal, we phase-folded the light curve according to its period and epoch. Close visual examination of each signal revealed no credible transit-like signal. After checking the original light curves, most were determined to be caused by edge effects from poorly corrected systematics in the original data. The other signals are spurious for undetermined reasons, but could potentially be attributed to improperly detrended light curves, poor transit subtraction, TTVs, or statistical noise.

5. VISUAL SEARCH FOR PLANETS

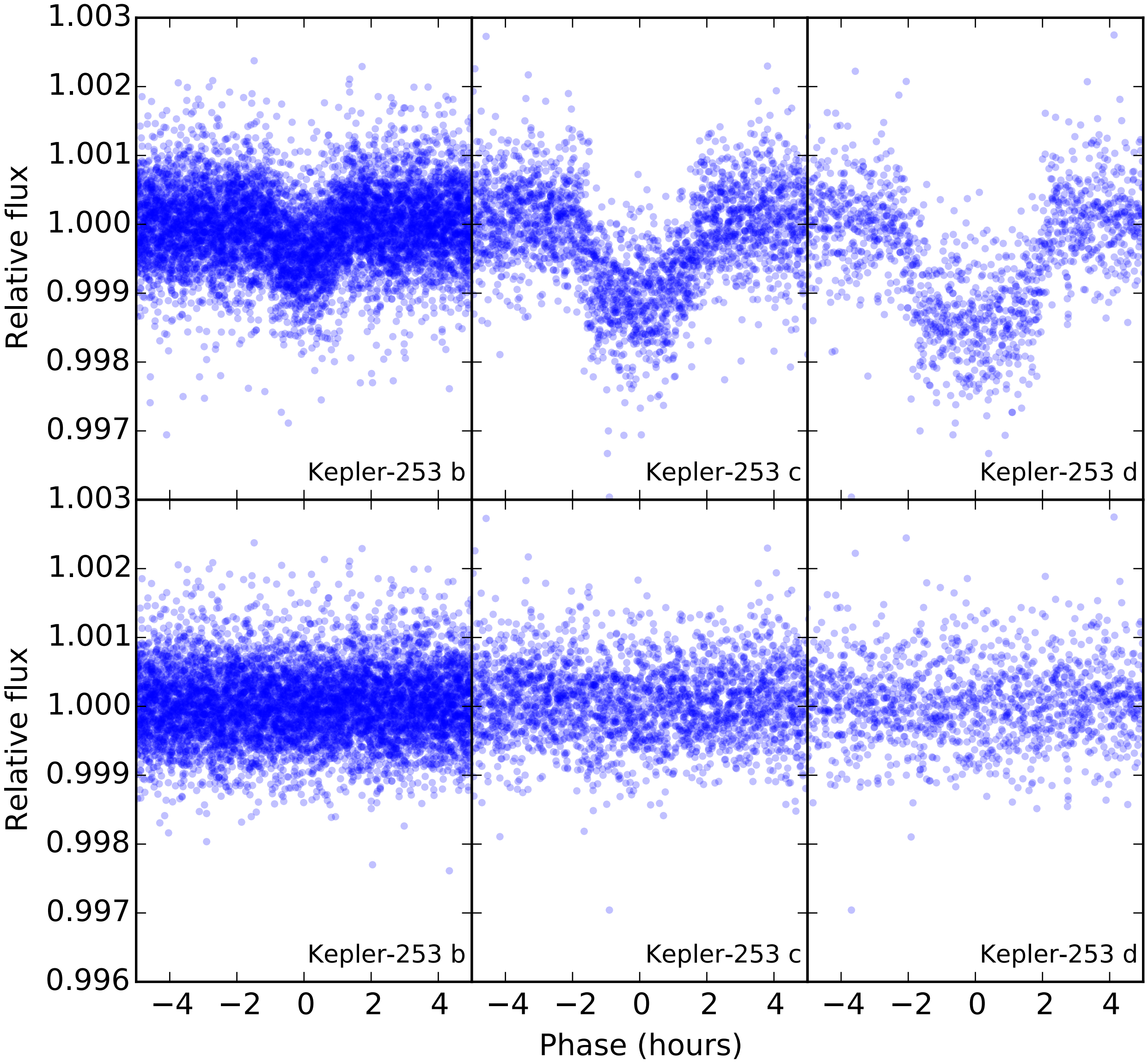

Figure 3. Phase-folded light curve for all three CPs in Kepler-253. *Top:* After detrending, but before transit subtraction. *Bottom:* After detrending and transit subtraction. Data points are transparent to emphasize the transit shape.

Exoplanet systems with multiple transiting planets are likelier than other systems to host more distant planets that also transit. Some of these will only transit once or twice in the *Kepler* data, which are frequently missed by automated search algorithms. While large planets with 1-2 transits can be easy to spot visually, these transits could easily be missed or overlooked in the forest of transits from known planets. Light curves that are flattened, normalized, and have known transits subtracted out should then make these planets with 1-2 transits stand out more clearly. Therefore, we visually inspected all the transit-subtracted light curves for additional transit signals. Three new potential transits were found around two stars.

5.1. *Kepler-150*

Two highly significant transits were found in the light curve of Kepler-150 and belong to a new planet, Kepler-150 f. The transits are visually apparent in both the PDCSAP flux and the raw SAP flux. The second transit slightly overlaps with the transit of another planet in the system, but this was corrected for in the earlier transit subtraction. A visual check confirms that there is no shorter period possible in the data.

The transits were fit with the IDL program `TAP` (Gazak et al. 2012), which is a Markov Chain Monte Carlo (MCMC) transit fitter that uses EXOFAST (Eastman et al. 2013) to calculate transit models (Mandel & Agol 2002) using a wavelet-based likelihood function (Carter & Winn 2009). `TAP` fits for the basic transit parameters such as the ratio of planet radius to stellar radius $R_{\rm P}/R_*$, the transit duration T, the impact parameter b, the midtransit times, and quadratic and linear limb darkening, in addition to white and red noise and a quadratic function to correct for improper normalization. A circular orbit is assumed. Ten MCMC chains of length 200,000 were used to fit the transits. The

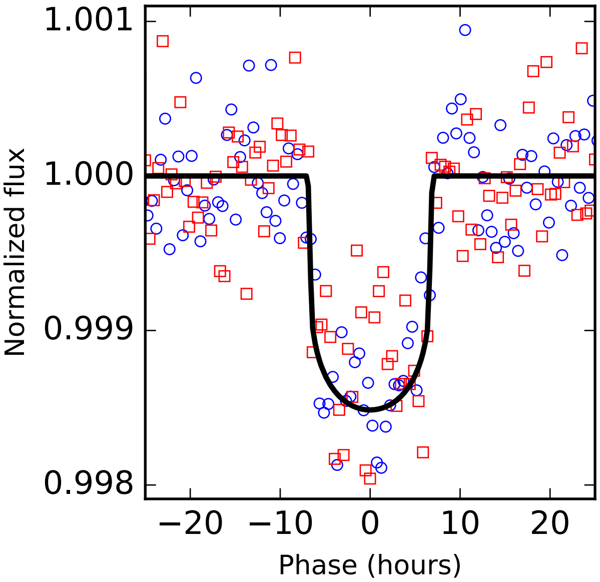

Figure 4. Phase-folded, flux-normalized light curve for Kepler-150 f. Transits by other planets in this window were modeled and subtracted out. Blue circles show the first transit, while red squares show the second. The black line is the best fit from `TAP`.

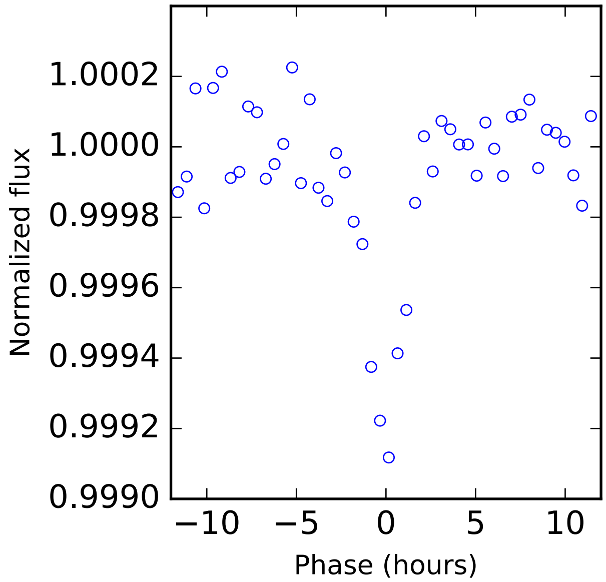

Figure 5. Potential single transit in the light curve of Kepler-208 at 786.7641 BKJD. Due to its likely nature as a background eclipsing binary FP, we did not attempt a transit fit.

length was picked so as to satisfy the Gelman-Rubin statistic (Gelman & Rubin 1992) that tests for non-convergence. The planet radius and semi-major axis were calculated using the R_P/R_* and derived a/R_* best-fit values from `TAP` and the stellar radius from the KOI catalog cumulative list accessed January 5, 2017 ($R_* = 0.931^{+0.377}_{-0.106}$ R$_\odot$), assuming pseudo-Gaussian errors. The reported best-fit values in Table 1 are the median values plus or minus 1σ error bars. The phase-folded, fitted light curve is shown in Figure 4.

Three arguments are used to confirm Kepler-150 f. First, the fact that Kepler-150 f is found in a system with four other confirmed planets argues strongly that it is not a FP. According to Lissauer et al. (2012), "almost all of *Kepler*'s multiple-planet candidates are planets". They calculate that there should be < 1 FP in all systems with 2+ PCs. The expected number of FPs for systems with 4+ PCs like Kepler-150 would be even lower.

Secondly, all planets in the Kepler-150 system were tested to see if their periods and transit durations were consistent with orbiting the same star. This transit duration analysis has been used previously as an additional level of vetting (Steffen et al. 2010; Lissauer et al. 2012; Chaplin et al. 2013; Cabrera et al. 2014). In a perfectly coplanar, circular, edge-on system, and assuming that the planets' radii and masses are much smaller than that of the star's, the transit duration T and the period P of the planets are, for any pair of planets, related according to the formula $T_i/P_i^{1/3} = T_j/P_j^{1/3}$, where the i and j indices refer to any two planets in the system. The values for $T_{b,c,d,e}$ and $P_{b,c,d,e}$ were taken from the KOI catalog, while T_f and P_f were determined by `TAP`. The $T/P^{1/3}$ values are highly consistent with each other with no planet being $> 1.6\%$ different from the average value. This strongly indicates that all five planets orbit the same star and also suggests that they have nearly circular orbits.

Lastly, we performed an analysis with the Python program `vespa` (Morton 2012, 2015; Morton et al. 2016), which calculates a false positive probability (FPP) for three scenarios of FPs: an eclipsing binary, a hierarchical eclipsing binary, and a background eclipsing binary. The `vespa` analysis of Kepler-150 f determines its false positive probability to be 0.69%. This does not taken into account either the planet multiplicity argument or the transit duration arguments above.

Combining all three arguments together results in a FPP that is $\ll 1\%$, confirming Kepler-150 f as a true exoplanet. It is approximately the size of Neptune with a planet radius $R_P = 3.86^{+1.38}_{-0.61}$ R$_\oplus$and a period $P = 637.2094^{+0.0164}_{-0.0152}$ days.

5.2. *Kepler-208*

Two potential single transits were discovered in Kepler-208, a system with four confirmed planets. However, one transit has been previously discovered at Barycentric Kepler Julian Date[3] BKJD = 786.7641 by Uehara et al. (2016), who performed their own visual checks of KOI systems. The other transit is highly suspect. The potential new transit is sharply V-shaped (see Figure 5) and has a short duration of just $T = 2.65$ hours. Its morphology is most consistent with a single transit of a background eclipsing binary, although there is a slight possibility that this could be a large, distant planet in a glancing transit. However, because it is likely a FP, we performed no further analysis of this transit.

6. DISCUSSION

[3] To convert to Barycentric Julian Date (BJD), use the formula BJD = BKJD + 2, 454, 833.0

Table 1
Kepler-150 f properties.

Parameter	Best-fit value	Unit
Period (P)	$637.2094^{+0.0164}_{-0.0152}$	days
Impact parameter (b)	$0.00^{+0.77}_{-0.76}$	
Inclination (i)	$89.9^{+0.1}_{-0.2}$	deg
Duration (T)	$13.41^{+0.59}_{-0.38}$	hours
Planet radius to stellar radius ratio ($R_{\rm P}/R_*$)	$0.0358^{+0.0041}_{-0.0022}$	
Semi-major axis to stellar radius ratio (a/R_*)	$291.1^{+62.9}_{-106.5}$	
First midtransit time	$509.0334^{+0.0125}_{-0.0148}$	BKJD
Second midtransit time	$1146.2422^{+0.0082}_{-0.0077}$	BKJD
Planet radius ($R_{\rm P}$)	$3.86^{+1.38}_{-0.61}$	$R_\oplus$
Semi-major axis (a)	$1.30^{+0.53}_{-0.47}$	AU

Note. — Best-fit results from the `TAP` transit fit. Reported values are the median and the upper and lower 1σ error bars. The planet radius and semi-major axis were calculated using the stellar radius from the KOI catalog ($R_* = 0.931^{+0.377}_{-0.106}$ $R_\odot$), assuming pseudo-Gaussian errors. Eccentricity was held fixed at zero.

It was not unexpected that these missing planets would be rare. There are two reasons why masking out data may result in losing planets. One reason is that it could reduce the number of detectable transits from 3+ to < 3. However, the parameter space for which this would occur is small to begin with. Planets with periods around 400-500 days (for stars with a full $\sim$ 1470 day baseline) are the most susceptible to be lost because these are likely to transit exactly three times. Due to geometry, planets with $P = 400 - 500$ days are not likely to transit in the first place. If such a planet were to transit though, then even a single overlapping transit could remove it from detectability. However, even an overlapping transit would be no guarantee. Long-period planets typically have longer durations. Therefore, if they overlap with a short-period planet, which is the most likely overlapping scenario, then only a small portion of the long-period planet's transit is removed, which would allow it to still be detectable. In order to remove enough of the long-period transit to render it undetectable, either a) it would need to overlap with another fairly long-period planet, b) two or more short-period planets would need to overlap the same long-period transit in different spots, or c) a short-period planet and a data gap would need to overlap the same long-period transit in different spots. Each of these requires an unlikely confluence of events.

A minor confounding factor would be the relative impact parameters of the planets with overlapping transits. Since planetary systems are usually flat with small scatter, inner planets are likelier to have lower impact parameters than outer planets in the system. Higher impact parameters result in shorter durations. Therefore, it is possible, although unlikely, that the transit duration of the longer period planet would be shorter than (or, at least, comparable to) that of a shorter period planet in the same system. This would make overlapping a larger portion of the long-period planet's transit easier and thus could more easily render the long-period planet undetectable.

A second way that masking out data may result in losing planets is for weak transit signals that were on the verge of detectability in the first place. The Multiple Event Statistic (MES) is the signal-to-noise of a transit signal in the *Kepler* pipeline (Jenkins et al. 2002). TPS requires a minimum MES of 7.1 for detection and classification as a TCE (Jenkins et al. 2010b; Tenenbaum et al. 2012). Removing a full transit or even small portions of a transit could result in the MES dropping below this threshold, thus rendering the planet lost. Subtracting out previously found transits rather than removing the data points altogether may keep the MES > 7.1. On one hand, this might be hard to promote to PC or CP status anyway since the FP population is dominated by TCEs with three transits and a low MES (Mullally et al. 2015). On the other hand, the fact that these systems already have 3+ CPs imply that these three transit, low MES cases could be more easily proven to be planets through statistical validation (Lissauer et al. 2012). Note that our simulation of planets in Section 2 did not test for this.

A visual search of the data, however, resulted in the discovery of Kepler-150 f. This makes Kepler-150 just one of 25 stars to host at least five exoplanets, according to the NASA Exoplanet Archive (Akeson et al. 2013). The demise of the main *Kepler* mission, however, has made additional follow-up study of this system difficult. A radial velocity measurement, for example, would be challenging with its long period ($P = 637.2$ days) and an expected radial velocity semi-amplitude of just 1.37 m/s, assuming a Neptune-mass planet.

7. CONCLUSION

A simulation of millions of planets around 114 stars with 3+ confirmed planets showed that there is a low, but non-negligible probability of transiting planets being lost after transit masking of known KOIs (about 3.3% of transiting planets in the period range of $P = 400 - 500$ days). We searched these same stars for new planetary transits, but instead of masking out transits of known KOIs, we fit and subtracted them out. However, our search discovered no credible new transit signals, which was consistent with our simulations.

The original purpose of masking out known in-transit data points rather than subtracting them out was due to the fact that the subtraction process produced a large number of FPs due to improper subtraction. This made it impractical to do in a time-intensive analysis such as the *Kepler* pipeline despite the risk that it would cause planets to be missed. Our analysis, however, demonstrates the validity and robustness of the *Kepler* pipeline's choice to use transit masking over transit subtraction.

However, a visual follow-up of the transit-subtracted light curve revealed the existence of a Neptune-sized exoplanet, Kepler-150 f (R_P = 3.86 $R_\oplus$), making Kepler-150 one of the few stars with 5+ known planets. Because of its long period ($P = 637.2$ days), only two transits are contained in the data, which made it undetectable to the *Kepler* pipeline. The authors contribute its discovery to the subtraction of known planet transits from the light curve. This discovery suggests the possibility that improved light curve flattening and transit subtraction, or simply better eyes, may result in the discovery of new, long period exoplanets.

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REFERENCES

Akeson, R. L., Chen, X., Ciardi, D., et al. 2013, PASP, 125, 989
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Science, 327, 977
Cabrera, J., Csizmadia, S., Lehmann, H., et al. 2014, ApJ, 781, 18
Carter, J. A., & Winn, J. N. 2009, ApJ, 704, 51
Chaplin, W. J., Sanchis-Ojeda, R., Campante, T. L., et al. 2013, ApJ, 766, 101
Coughlin, J. L., Mullally, F., Thompson, S. E., et al. 2016, ApJS, 224, 12
Eastman, J., Gaudi, B. S., & Agol, E. 2013, PASP, 125, 83
Fischer, D. A., Schwamb, M. E., Schawinski, K., et al. 2012, MNRAS, 419, 2900
Gazak, J. Z., Johnson, J. A., Tonry, J., et al. 2012, Advances in Astronomy, 2012, 30
Gelman, A., & Rubin, D. B. 1992, StaSc, 7, 457
Holczer, T., Mazeh, T., Nachmani, G., et al. 2016, ApJS, 225, 9
Jenkins, J. M., Caldwell, D. A., & Borucki, W. J. 2002, ApJ, 564, 495
Jenkins, J. M., Caldwell, D. A., Chandrasekaran, H., et al. 2010a, ApJ, 713, L87
Jenkins, J. M., Chandrasekaran, H., McCauliff, S. D., et al. 2010b, in Proc. SPIE, Vol. 7740, Software and Cyberinfrastructure for Astronomy, 77400D
Lintott, C. J., Schwamb, M. E., Barclay, T., et al. 2013, AJ, 145, 151
Lissauer, J. J., Marcy, G. W., Rowe, J. F., et al. 2012, ApJ, 750, 112
Mandel, K., & Agol, E. 2002, ApJ, 580, L171
Mazeh, T., Nachmani, G., Holczer, T., et al. 2013, ApJS, 208, 16
Morton, T. D. 2012, ApJ, 761, 6
—. 2015, VESPA: False positive probabilities calculator, Astrophysics Source Code Library, ascl:1503.011
Morton, T. D., Bryson, S. T., Coughlin, J. L., et al. 2016, ApJ, 822, 86
Mullally, F., Coughlin, J. L., Thompson, S. E., et al. 2015, ApJS, 217, 31
Rowe, J. F., Bryson, S. T., Marcy, G. W., et al. 2014, ApJ, 784, 45
Schmitt, J. R., Wang, J., Fischer, D. A., et al. 2014a, AJ, 148, 28
Schmitt, J. R., Agol, E., Deck, K. M., et al. 2014b, ApJ, 795, 167
Schmitt, J. R., Tokovinin, A., Wang, J., et al. 2016, AJ, 151, 159
Schwamb, M. E., Orosz, J. A., Carter, J. A., et al. 2013, ApJ, 768, 127
Seader, S., Jenkins, J. M., Tenenbaum, P., et al. 2015, ApJS, 217, 18
Smith, J. C., Stumpe, M. C., Van Cleve, J. E., et al. 2012, PASP, 124, 1000
Steffen, J. H., Batalha, N. M., Borucki, W. J., et al. 2010, ApJ, 725, 1226
Still, M., & Barclay, T. 2012, PyKE: Reduction and analysis of Kepler Simple Aperture Photometry data, Astrophysics Source Code Library, ascl:1208.004
Stumpe, M. C., Smith, J. C., Van Cleve, J. E., et al. 2012, PASP, 124, 985
Tenenbaum, P., Christiansen, J. L., Jenkins, J. M., et al. 2012, ApJS, 199, 24
Tenenbaum, P., Jenkins, J. M., Seader, S., et al. 2013, ApJS, 206, 5
—. 2014, ApJS, 211, 6
Twicken, J. D., Jenkins, J. M., Seader, S. E., et al. 2016, AJ, 152, 158
Uehara, S., Kawahara, H., Masuda, K., Yamada, S., & Aizawa, M. 2016, ApJ, 822, 2
Wang, J., Fischer, D. A., Barclay, T., et al. 2013, ApJ, 776, 10
—. 2015, ApJ, 815, 127

Table 2
Stars with 3+ confirmed used in this study.

Kepler name	KIC	Number of confirmed planets (not fit)	Number of KOI candidates (not fit)	Name of non-fitted planets and KOIs
Kepler-11	6541920	6	0	
Kepler-18	8644288	3	0	

Table 2 — Continued

Kepler name	KIC	Number of confirmed planets (not fit)	Number of KOI candidates (not fit)	Name of non-fitted planets and KOIs
Kepler-20	6850504	5	0	
Kepler-30	3832474	3	0	
Kepler-31	9347899	3	1	
Kepler-33	9458613	5	0	
Kepler-37	8478994	3	0	
Kepler-42	8561063	3	0	
Kepler-48	5735762	3	0	
Kepler-49	5364071	4	0	
Kepler-52	11754553	3	0	
Kepler-53	5358241	3	0	
Kepler-54	7455287	3	0	
Kepler-55	8150320	5 (1)	0	Kepler-55 c
Kepler-58	4077526	3	1	
Kepler-60	6768394	3	0	
Kepler-62	9002278	5	0	
Kepler-65	5866724	3	0	
Kepler-79	8394721	4	0	
Kepler-80	4852528	4	1	
Kepler-81	7287995	3	0	
Kepler-82	7366258	4	0	
Kepler-83	7870390	3	0	
Kepler-84	5301750	5	0	
Kepler-85	8950568	4	0	
Kepler-89	6462863	4	0	
Kepler-102	10187017	5	0	
Kepler-104	6678383	3	0	
Kepler-107	10875245	4	0	
Kepler-114	10925104	3	0	
Kepler-122	4833421	5	0	
Kepler-124	11288051	3	0	
Kepler-127	9451706	3	0	
Kepler-130	5088536	3	0	
Kepler-132	6021275	3	1	
Kepler-138	7603200	3	0	
Kepler-142	10982872	3	0	
Kepler-149	3217264	3	0	
Kepler-150	5351250	4	0	
Kepler-164	10460984	3	1 (1)	KOI 474.03
Kepler-169	5689351	5	0	
Kepler-171	6381846	3	0	
Kepler-172	6422155	4	0	
Kepler-174	8017703	3	0	
Kepler-176	8037145	3	1	
Kepler-178	9941859	3	0	
Kepler-184	7445445	3	0	
Kepler-186	8120608	5	0	
Kepler-194	10600261	3	0	
Kepler-197	12068975	4	0	
Kepler-203	6062088	3	0	
Kepler-206	6442340	3	0	
Kepler-207	6685609	3	0	
Kepler-208	7040629	4	0	
Kepler-215	8962094	4	0	
Kepler-219	9884104	3	0	
Kepler-220	9950612	4	0	
Kepler-221	9963524	4	0	
Kepler-222	10002866	3	0	
Kepler-223	10227020	4 (1)	0	Kepler-223 e
Kepler-224	10271806	4	0	
Kepler-226	10601284	3	0	
Kepler-228	10872983	3	0	
Kepler-229	10910878	3	0	
Kepler-235	4139816	4	0	
Kepler-238	5436502	5	0	
Kepler-244	6849310	3	0	
Kepler-245	6948054	3 (2)	1	Kepler-245 b, Kepler-245 d
Kepler-249	7907423	3	0	
Kepler-250	8226994	3	0	
Kepler-251	8247638	4	0	
Kepler-253	8689373	3	0	
Kepler-254	9334289	3	0	
Kepler-256	9466668	4	0	
Kepler-257	9480189	3	0	
Kepler-265	5956342	4	0	
Kepler-267	10166274	3	0	

Table 2 — Continued

Kepler name	KIC	Number of confirmed planets (not fit)	Number of KOI candidates (not fit)	Name of non-fitted planets and KOIs
Kepler-272	10426656	3	0	
Kepler-275	3447722	3	1 (1)	KOI 1198.04
Kepler-276	3962243	3	0	
Kepler-282	8609450	4	0	
Kepler-286	10858691	4	0	
Kepler-288	4455231	3	0	
Kepler-292	6962977	5	0	
Kepler-295	9006449	3 (1)	0	Kepler-295 d
Kepler-296	11497958	5 (1)	0	Kepler-296 e
Kepler-298	11176127	3	0	
Kepler-299	11014932	4	0	
Kepler-301	11389771	3	0	
Kepler-304	5371776	3	1	
Kepler-305	5219234	3	1	
Kepler-306	5438099	4	0	
Kepler-310	10004738	3	0	
Kepler-325	9471268	3	0	
Kepler-327	8167996	3	0	
Kepler-331	4263293	3	0	
Kepler-332	10328393	3	0	
Kepler-334	10130039	3	0	
Kepler-336	6037581	3	0	
Kepler-338	5511081	4	0	
Kepler-339	10978763	3	0	
Kepler-341	7747425	4	0	
Kepler-342	9892816	3 (1)	1	
Kepler-350	4636578	3	0	
Kepler-354	6026438	3	0	
Kepler-357	8164257	3 (1)	0	Kepler-357 d
Kepler-363	6021193	3	0	
Kepler-372	11401767	3	0	
Kepler-374	6871071	3	2	
Kepler-399	5480640	3	0	
Kepler-402	7673192	4	1	
Kepler-444	6278762	5	0	
Kepler-445	9730163	3	0	
Kepler-446	8733898	3	0	

Note. — Stars included in this study, each with 3+ CPs. Some also have additional PCs. The column "Number of confirmed planets (not fit)" refers to the number of CPs in that system, while the number in the parentheses, if applicable, are how many of those CPs were unable to be fit. The column "Number of KOI candidates (not fit)" is similar, but for PCs that have not been confirmed. The names of the non-fitted KOIs are in the last column.