DETECTION OF POTENTIAL TRANSIT SIGNALS IN THE FIRST THREE QUARTERS OF Kepler MISSION DATA

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ABSTRACT

We present the results of a search for potential transit signals in the first three quarters of photometry data acquired by the Kepler mission. The targets of the search include 151,722 stars which were observed over the full interval and an additional 19,132 stars which were observed for only one or two quarters. From this set of targets we find a total of 5392 detections which meet the Kepler detection criteria: those criteria are periodicity of signal, an acceptable signal-to-noise ratio, and a composition test which rejects spurious detections which contain non-physical combinations of events. The detected signals are dominated by events with relatively low signal-to-noise ratio and by events with relatively short periods. The distribution of estimated transit depths appears to peak in the range between 40 and 100 parts per million, with a few detections down to fewer than 10 parts per million. The detections exhibit signal-to-noise ratios from 7.1σ, which is the lower cutoff for detections, to over 10,000σ, and periods ranging from 0.5 days, which is the lower cutoff in the procedure, to 109 days, which is the upper limit of achievable periods given the length of the data set and the criteria used for detections. The detected signals are compared to a set of known transit events in the Kepler field of view which were derived by a different method using a longer data interval; the comparison shows that the current search correctly identified 88.1% of the known events. A tabulation of the detected transit signals, examples which illustrate the analysis and detection process, a discussion of future plans and open, potentially fruitful, areas of further research are included.

Key words: planetary systems – planets and satellites: detection

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The Kepler mission (Borucki et al. 2010) uses a space-based photometer with a 115 deg2 field of view to search for transit signatures of extrasolar planets, with a particular emphasis on Earth-size planets situated in the habitable zones of their parent stars. Transit signatures are characterized by periodic reductions in observed brightness as the planet blocks light from the star.7 While Jovian-sized transiting exoplanets typically produce a transit signature on the order of 1% in relative flux, which can be detected by relatively simple algorithms, a true Earth-analog orbiting a solar-type star is much more difficult to detect: its transits can result in brightness reductions of 100 parts per million (PPM) or less, and the resulting reductions typically last for 1–13 hr and repeat approximately once per year. Given the large number of objects which are observed by Kepler, the long data sets implied by the need for multi-year observation on sub-hour cadence, and the miniscule reductions in intensity expected for small, rocky inner planets, one of the key data processing requirements for the Kepler mission is an automated search for signals which are consistent with transiting planets. This is the task of the Transiting Planet Search (TPS) software module (Jenkins 2002; Jenkins et al. 2010).

This study describes the results of searching Kepler observations acquired during the first 218 days of science operations with the TPS software module.

1.1. Kepler Science Data

The Kepler photometer maintains a constant pointing centered on α = 19h22m40s, δ = +44°5. In order to permit nearly continuous observation of its fixed field of view, the Kepler photometer utilizes an Earth-trailing heliocentric orbit. The requirement that Kepler maintains its solar panels pointing at the Sun and its thermal radiator pointing away from the Sun implies that Kepler must rotate about its axis by 90° four times per solar orbit of 372 days. The focal plane has been constructed with near-perfect 90° rotational symmetry to minimize disruption of the observations due to these rotations. An observational period at a fixed axial rotation angle is referred to as a “quarter” and the maneuver from one rotation angle to another is referred to as a “quarterly roll.”

The data acquisition period selected for this analysis spans the first three quarters (Q1–Q3) of science observation, spanning the interval from 2009 May 12 00:00:00 UTC to 2009 December

7 In the case of multi-body systems, for example, multiple planets orbiting a single star, gravitational interactions can break the perfect periodicity of the orbits, leading to transit timing variations (TTVs). See Sections 2 and 4 for more information about the detection of planets which exhibit TTV.
17:23:59.9 UTC, a total period of 218 days. The first “quarter” consisted of approximately 33.4 days of data acquisition following the end of spacecraft commissioning; the second and third quarters each contain approximately 89 days of data acquisition. Thus the total acquisition time is 211.4 days, the balance being taken up by quarterly rolls and by a safe-mode event which was immediately adjacent to a quarterly roll. During data acquisition, photometric data are taken with 6.0 s integrations, with each integration followed by a 0.5 s readout time; these integrations are summed on board into 29.4 minute “long cadence” intervals. The three quarters under discussion span a total of 10,363 such long cadences. In addition to the aforementioned data gaps in the quarterly roll intervals, there are additional intra-quarter gaps due to spacecraft anomalies, reaction wheel desaturation in the quarterly roll intervals, there are additional intra-quarter gaps that is presented to the TPS module.

In order to limit the volume of downlinked data to acceptable levels, Kepler only acquires and downlinks photometric data for a small subset of pixels (i.e., 5.44 million or fewer pixels out of 94.6 million pixels on the focal plane). The pixels are pre-selected in order to optimally capture the light from target stars.

### 1.2. Pre-search Processing

The pixel data from the spacecraft are processed by the *Kepler* photometry pipeline prior to the search for transiting planet signals. The first processing step is performed by the Calibration (CAL) module (Quintana et al. 2010). Calibration includes detection and removal of cosmic rays in collateral (non-science) pixels, correction for variations in pixel sensitivity, removal of detector bias and dark current effects, removal of smear artifacts introduced by shutterless operation, and removal of distortions introduced by the readout electronics. Following calibration, the Photometric Analysis (PA) module (Twicken et al. 2010b) assembles the data from individual pixels into flux time series for each target. This includes performing aperture photometry on the calibrated pixels associated with each target, estimation and removal of backgrounds, and detection and removal of cosmic rays in science pixels. The flux time series from PA are then processed by the Pre-Search Data Conditioning (PDC) module (Twicken et al. 2010a). The PDC module performs a number of error corrections upon each flux time series. The corrections include compensation for effects which are systematic across the focal plane, such as changes in flux due to pointing variation, differential velocity aberration, focus changes, and thermal transients; there are also corrections which are specific to each target, such as removal of step discontinuities due to cosmic ray damage to individual CCD pixels and removal of excess flux due to aperture crowding. Finally, PDC fills gaps introduced by intra-quarter spacecraft anomalies or operations.

The processing steps described above are performed on a quarterly basis and result in piecewise-continuous flux time series with inter-quarter gaps that is presented to the TPS module. The data conditioning steps described above are intended to remove all sources of flux variation with the exception of astrophysical phenomena and uncorrelated instrument and statistical noise.

### 1.3. Post-search Analysis

The procedure for discovery of extrasolar planets does not end with the detections produced by the TPS algorithm as described in Section 2. The detections from TPS are further analyzed by the Data Validation (DV) module (Wu et al. 2010). DV performs a number of automated tests which assist in evaluating the probability that a TPS detection is an extrasolar planet.

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Note: As noted in the text, the transit depth values are an approximation. Published KOIs are indicated by a number in the KOI column; published false positives are indicated by “FP” in the KOI column.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
The results of the DV tests are collected and presented to the Kepler science team. The DV module is the final automated step in the discovery process. All subsequent steps are labor-intensive and performed by members of the science team. The results from DV are examined and assessed, detections which are obviously not due to astrophysical phenomena are eliminated, and the remainder are classified as Kepler Objects of Interest (KOIs; Borucki et al. 2011). Further analysis of the KOIs permits them to be sorted into one of several categories: likely planet detections, eclipsing binary stars, false positives (typically background eclipsing binaries), and other detections which evade classification. The likely planet detections are prioritized and subjected to follow-up observations using a wide variety of ground-based and space-based instruments. The follow-up observations will permit validation of some of the likely planet detections, while others will be revealed as additional false-positive detections.

As the foregoing description shows, it is not possible to classify TPS detections without considerable subsequent analysis and additional measurements from other instruments. In the remainder of this paper, we will consider the full complement of TPS detections in the Q1–Q3 data set; as the majority of these have not yet received the necessary “person-in-the-loop” analysis, it is not possible to say with any certainty which ones are likely to be signals from extrasolar planets and which ones are likely to be some form of false positive. It is anticipated that the presented information on the full set of detections will assist researchers by guiding them to target stars in the Kepler field of view which are thought to be of the greatest interest from the viewpoint of transiting objects. The table can also be used as a catalog of known detections, so that future detections of candidates by other researchers using other techniques can determine whether their detection corroborates a known event or represents a potentially heretofore-unknown event.

2. TRANSITING PLANET SEARCH

The TPS module is described in some detail elsewhere (Jenkins 2002; Jenkins et al. 2010), and we briefly summarize its main features and actions here.

As described in Section 1.2, the processing steps prior to TPS invocation all operate on data from one quarter at a time. Thus, the first task of TPS is to combine the flux time series from several quarters into a single flux time series suitable for searching. This “quarter-stitching” procedure is as follows.

1. The data from each quarter are converted from absolute flux in photoelectrons to fractional flux variation; this is accomplished by dividing each quarter’s flux by that quarter’s median flux value and subtracting 1.
2. Strongly sinusoidal variations are removed from the flux quarter by quarter: the variations are first identified by constructing a periodogram of the flux, and identifying well-separated peaks which are strong compared to an estimate of the noise at the selected frequency (the latter being determined from the power spectral density in the region surrounding each peak); the harmonics are then fitted via the Levenberg-Marquardt algorithm, with the amplitude, phase, and frequency of each harmonic as fit parameters; the fitted harmonics are then subtracted from the flux time series.

3. Any trends present in each quarter at the start and end of data acquisition are removed: a third-order polynomial is constructed which matches the average offset and slope of the flux time series in its first and last 49 cadences; subtracting this polynomial removes the net offset and slope from the ends of the time series, at the expense of introducing potentially large excursions to the remainder of the time series; these excursions are then removed by fitting a polynomial of the form \(x(1-x)p(x)\), where \(x\) is normalized time (i.e., \(x \equiv 0\) at the start of the quarter and \(x \equiv 1\) at the end) and \(p(x)\) is a conventional polynomial of the form \(p(x) = p_0 + p_1x + p_2x^2 + \ldots\); this process reduces the excursions while preserving the desired edge conditioning from the initial cubic polynomial subtraction; the polynomial order is determined through use of Akaike’s information criterion (Akaike 1974), subject to a user-selected limit (set to 10th order in this case).

4. Remaining data gaps are filled: this includes inter-quarter gaps and gaps which are a full quarter or longer due to incomplete observations for some targets; note that this is done in order to facilitate construction of a digital filter bank which is required for the subsequent analysis. The gap-filling algorithm is the same as the one used in PDC (Twicken et al. 2010a). A detailed description of the algorithm is beyond the scope of this paper, and in any event studies have indicated that the detection of transits depends only weakly on the gap-filling algorithm.

The second step in the TPS analysis process is to perform a detection of individual transits in the quarter-stitched flux time series. This process is complicated by the fact that the noise due to stellar variability is both non-white and non-stationary, indicating that a joint time-frequency analysis procedure will be required. The procedure is described in detail in Jenkins (2002) and is summarized in the Appendix. This results in a single event statistic (SES) time series: a time series which describes, for each sample in the original flux time series, the significance (in \(\sigma\)) of the detection of a transit-like signal centered on that sample. As shown in the Appendix, the algorithm is sensitive to the match in overall shape between the transits in the data and the model transit pulse used in the search; thus, the detection signal will be maximized when the duration of the latter is well matched to the duration of the former, and falls off when the two are mismatched in duration. The search is therefore performed repeatedly using a discrete set of different model transit durations in order to ensure sensitivity to all expected transit durations, and an SES time series is produced for each model transit duration used in the search. The number of transit durations used in the search is set by balancing the conflicting demands of maximum sensitivity to a wide variety of transit durations (which mandates a large number of searches, with small increments in trial transit pulse duration from one search to another) and computational tractability (which mandates a small number of searches). Additionally, the selected model transit durations must be comparable to the expected actual durations of planetary transits. Based on these requirements, each flux time series is searched for individual transit-like features with the following 14 durations: 1.5, 2.0, 2.5, 3.0, 3.5, 4.5, 5.0, 6.0, 7.5, 9.0, 10.5, 12.0, 12.5, and 15.0 hr.

The next step is to use the results of the search for individual transit-like features to search for transit-like features which are periodic. This is accomplished by combining or “folding” the SES across time into multiple event statistics (MES) according to Equation (A6). The periods which are used in each folding

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9 The exception to this is TPS detections which correspond to known KOIs, as discussed in Section 3.2.
are a compromise between small period spacing to minimize false negatives and large period spacing to minimize computing requirements (Jenkins et al. 1996). The set of periods is determined algorithmically during execution using specified values for the minimum and maximum periods and the desired model correlations between consecutive periods; for the purposes of this analysis, the minimum period used in folding was 0.5 days, and the maximum was the full duration of the data set, or 218 days. At each period, the search examines a set of possible phases, where the phase step is determined from the duration of the trial transit pulse in such a way as to provide a user-selected degree of correlation from one phase step to the next. The result of folding is a two-dimensional array of MES, one value for each combination of period and phase. These are collapsed along the phase axis to yield a vector of MES versus period, where the vector value represents the maximum of the MES versus phase for that particular period. It is at this point that gap-fills are suppressed from contributing to a detection: when a filled cadence is included in a fold, it is not permitted to contribute to the MES.

It is interesting to note that, while the process above is explicitly designed to find transit-like features which are periodic, the TPS algorithm has had reasonable success in detecting planet candidates which exhibit transit timing variations (TTVs) which cause their transit timings to depart from perfect periodicity. This is because TPS uses a dense grid of periods; if the individual transit signals are sufficiently large and the TTVs sufficiently small, detections can occur when the “wings” of the transits are folded over one another. Examples of this include Kepler-9b and -9c (Holman et al. 2010), and all of the Kepler-11 planets (Lissauer et al. 2011).

The final step is to perform cuts based on the results of the above analyses. The first and most important cut is to remove from further analysis any star for which all of the MES for all periods and all pulse durations fall below 7.1σ. The threshold value of 7.1σ was chosen as a compromise which simultaneously limits the number of expected false-positive detections due to pure statistical fluctuations, while on the other hand preserving sensitivity to Earth analogs (Jenkins et al. 2002). For the data set spanning the first three quarters, the number of stars which have at least one MES of at least 7.1σ is 66,593. Thus, this cut eliminates 104,261 targets from further analysis, or 61%. Figure 1 shows the period of each transit in days, and the epoch of each transit in Julian Date offset by 2,454,833 days (the so-called Kepler-modified Julian date or KJD). The strong features shown in Figure 1 are caused by a variety of known spacecraft events: reaction wheel desaturations, small adjustments in spacecraft attitude during data acquisition, and thermal transients due to the large change in spacecraft attitude required for monthly data downlinks.

The second cut makes use of the relationship between the maximum MES and the several SES which were combined to yield that MES. In particular, a threshold is established for the ratio of the MES and the largest participating SES. As Figure 2 shows, there are two distinct populations: a population with a low MES/SES ratio and a population with larger values of this ratio. The dividing line is at an MES/SES of approximately √2. The qualitative explanation for this distinction is as follows: in the case of a signal with two transits, in which the transits are of equal depth and occur against backgrounds of comparable noise, the ratio of MES/SES will be √2, and this ratio rises approximately as the square root of the number of transits, as shown in Equation (A6); when the ratio of MES/SES is lower than √2, this indicates that two highly unequal SES have been combined into an MES, a situation which is unlikely to occur in the case of transits of uniform depth and thus is unlikely to represent a true transit signal. For this reason, we apply a cut on the MES/SES ratio of 1.4142. This cut eliminates a large number of false positives which combine highly unequal SES into a MES, but also eliminates true positives which contain two transits of near-equal depth. Thus, the MES/SES cut is also an implicit cut on orbital period: a planet which has a period greater than half the duration of the data set will produce only two transits within the data set, which will yield an MES/SES ratio which is below the cutoff. The number of target stars which satisfy both the MES and the MES/SES criteria is 5392.

3. DETECTED SIGNALS OF POTENTIAL TRANSITING PLANETS

Figure 3 shows the epoch and period of the 5392 TPS detections. Note that, as compared with Figure 1, Figure 3 is devoid of strong features from spacecraft events; in addition, a number of spurious detections unrelated to spacecraft events are eliminated. However, the range of periods in Figure 3 is about half that of those in Figure 1, illustrating the implicit period limitation of the MES/SES cut. Figure 3 shows a relatively large number of detections with short periods, which is expected for two reasons: first, short-period signals will be relatively easier to detect than long-period signals of equal depth due to the larger number of transits within the Q1–Q3 interval and second, the probability of a planetary system’s inclination angle being such that the transits are visible to Kepler is inversely proportional to the semi-major axis of the planet’s orbit. Figure 3 also shows a small number of regions of parameter space which contain no detections. These are due to data gaps. For example, consider the region centered on an epoch of KJD 166 and periods of approximately 80 days. A signal with a period and an epoch in this region would have only three transits in the data interval which is presented here, one of which would fall within the long interval between Q1 and Q2 data acquisition; the remaining two transits would not pass the MES/SES ratio cut; therefore, no
signal which meets the *Kepler* detection criteria can have such a combination of parameters.

The most striking feature of Figure 3 is the three hard edges which bound all of the detections. The left-hand edge is due to the start of observations, since by definition no detection can have an epoch of first transit which precedes the start of observations. No detection can occur below the lower edge because any such detection has a period and epoch such that it would have a transit which occurs at an earlier epoch, which lies within the populated region (for example, a detection which has an epoch of KJD 150 and period 10 days is impossible, because such a detection would also have a transit at KJD 140, and so would be represented by a point at KJD 140 and period 10 days). The upper edge represents detections with three transits for which the third transit occurs in the last few cadences of Q3; a detection which lies above this edge is impossible because its third transit occurs after the end of Q3, and the remaining two transits would be eliminated by the MES/SES cut.

Figure 4 shows the detections as a function of period and MES. As with Figure 3, there is a gradient in detections which favors shorter periods over longer ones and weaker signals over stronger ones.

Figures 5 and 6 quantify the degree to which the distribution of detected signals is skewed toward weak signals and short periods. In Figure 5, we see the distribution of MES. Although the detections include signals as strong as 23,520 5σ, there are 4424 detections out of 5392 which have a maximum MES under 100σ, as shown in the left panel of Figure 5, and 3780 detections which have a maximum MES under 20σ, as shown in the right panel of Figure 5. Similarly, the left side of Figure 6 shows the period distribution of all detections; the right side of Figure 6 shows the period distribution of the 3732 detections which have periods under 15 days. It is interesting to note that, based on Figures 4–6, the number of detections in the first three quarters which could plausibly be detected using a single quarter’s worth of data is about 2400; the remaining 3000 detections possess periods too long or signals too weak to be detected using only a single quarter of data.

Although TPS does not directly compute the transit depth of each detection, it is possible to crudely estimate the transit depth. For each detection, the period and the epoch are used to identify the cadences which fall closest to the center of each transit; the noise characteristics at those cadences and the MES can be combined to yield an estimate of the transit depth. Because the trial transit pulse used by TPS is square rather than transit-shaped, and in general will not be precisely matched to the actual duration of the detected transit signature, the resulting estimate of transit depth (in PPM) is probably only reliable at the factor-of-two level, but it does give a general sense of whether the data set is dominated by deep or shallow transits.

Figure 7 shows the distribution of transit depths over three ranges: transit depths up to 1% (10,000 PPM), transit depths up to 0.1% (1000 PPM), and transit depths up to 0.01% (100 PPM). There are 4581, 3900, and 739 targets, respectively, in these distributions. The 712 targets which exhibit transit depths greater than 10,000 PPM form a long, diffuse tail which extends up to 415,000 PPM; these objects include a few super-Jovian planets and a large number of eclipsing binaries. Figure 8 shows the relationship between transit depth and period. It is both...
apparent and unsurprising that the smallest transits detected correspond to the shortest periods.

Of the 5392 targets with detected signals, 3815 of those targets were observed in all three quarters. Twelve detections were on targets observed in Q1 and Q2, 192 on targets observed in Q2 and Q3, 12 on targets observed on Q1 and Q3; 1035 on targets observed in Q1 only, 291 on targets observed in Q2 only, and 35 on targets observed in Q3 only. The large number of detections on targets observed only in Q1 is possibly explained by the fact that most of the targets which were removed from the observation list after Q1 were red giants. The oscillations which are a characteristic of red giants produce false-positive detections in TPS: these oscillations are in an unfortunate amplitude regime, in which they are too weak to trigger the harmonic removal procedure described in Section 2, but are still strong enough to trigger detection by the main TPS algorithm. It is entirely possible that some of the detections on targets observed only in Q1 are actual transiting planet signatures, but at this time the TPS algorithm has no means to distinguish between a true detection and this form of false positive.

Table 1 shows a complete list of detections in the first three quarters of Kepler data. The printed version shows only the first 10 detections, while the online version shows the full 5392. Table 1 includes all of the detections on stars observed only in Q1, though this set of detections is thought to be dominated by false positives. The uncertainty shown for transit depth is the statistical uncertainty, which is determined by the signal-to-noise ratio (S/N) of the detection, and does not include the systematic biases due to mismatches between the model transit and the actual transit in shape and duration, as described above.
Figure 6. Histogram of periods of detected signals. Left: all 5392 detections. Right: 3732 out of 5392 detections with period under 15 days. The hard edge at 0.5 days is due to the selection of this as the minimum search period for the study.

Figure 7. Transit depths. Top: 4581 detected signals with transit depths up to 10,000 PPM. Middle: 3900 detected signals with transit depths up to 1000 PPM. Bottom: 739 detected signals with transit depths up to 100 PPM.
3.1. Example Target Data Sets and Processing

Figures 9–12 show examples of Kepler light curves, and the process for analyzing the light curves and detecting the signals of transiting planets.

Figures 9 and 10 show the analysis of Kepler Input Catalog (KIC) 2309719, a star with Kepler magnitude 12.9 that was observed in all three quarters. This target contains a transit signature which is large enough to be seen with the unaided eye: a 1.1% depth with a period of 54.36 days. The top plot of Figure 9 shows the original flux time series, with intra-quarter gap-filled values in red and data values in blue. The middle plot of Figure 9 shows the quarter-stitched flux time series; in this case, both intra- and inter-quarter gap-filled values are in red. The bottom plot of Figure 9 shows the SES time series for this target, using a trial transit duration of 3.5 hr. In all three time series, the signature of the repeating transit event is easily detected by observation.

The top plot of Figure 10 shows the maximum MES as a function of period, again using a trial transit duration of 3.5 hr. The peak at 54.36 days is clearly visible, as is a slightly lower peak at three times the actual period. The peaks at periods shorter than 54.36 days are at periods which are harmonically related to the actual period: for example, folding the data at a period of 40.77 days will fold the first and last actual transits on top of one another, resulting in an increase in MES relative to periods which cause the first and last transits to “miss” one another in folding. Similarly, there is a continuum of values which are above the 7.1σ threshold because a single transit can have a significance as large as 100σ, as shown in Figure 9; thus, folding a single transit on top of several noise-dominated samples can easily exceed 7.1σ. The middle plot of Figure 10 shows the whitened flux time series for KIC 2309719: note that the structure which is evident in Q2 of the quarter-stitched original flux, in the middle plot of Figure 9, has been removed by the whitener, and that the shape of the transits has been distorted, with positive excursions occurring prior to and preceding the transit; these positive excursions in the whitened flux time series result in negative excursions in the SES time series in Figure 9. Green, dashed vertical lines in this plot indicate the expected transit locations based on the period and epoch of the detection, and as expected they coincide with the visible transit signatures. Finally, the bottom plot of Figure 10 shows the whitened flux time series after it has been folded at the detection period of 54.36 days, collected into 29.4 minute (one long cadence exposure) wide time bins, summed within bins, rescaled to unit variance, and zoomed in upon the phase of the transit. As expected, when processed in this manner the transit signature is clearly visible to casual observation.

Figures 11 and 12 show the same series of plots which follow the processing of KIC 2010191, a star with Kepler magnitude 14.6 which was observed in all three quarters. In this case, the maximum MES occurs for a trial transit duration of 2.5 hr. This target contains a transit signature which is too small to be discerned with the unaided eye, with a depth of approximately 285 PPM and 3.43 day period. Although the plot of maximum MES (top plot of Figure 12) clearly shows a detection at the 3.43 day period, the event only becomes apparent in the folded, binned, and summed version of the whitened flux time series, in the bottom of Figure 12.
3.2. Comparison with Known Kepler Objects of Interest

The optimal means of assessing the reliability of TPS detections is to introduce into TPS a set of flux time series which contains a known population of transit-like events, and compare the resulting detections to that known population. Under current circumstances this is not possible, since the only source of flux time series which sufficiently resembles the real behavior of stars is the actual stars in the Kepler field of view, and determining which of these stars have transiting planets is the goal of the mission—the unknown which we seek to make known. Nonetheless, at this time it is possible to perform a partial test of TPS by comparing the TPS detections to the current list of KOIs (Borucki et al. 2011). The KOI list is a set of transit detections which have been investigated in detail by the Kepler science team using a variety of techniques, and represents our best current knowledge of astrophysical signals in the Kepler field of view. Importantly, none of the KOIs were detected using the multi-quarter TPS algorithm described above, but were instead detected using a variety of alternate methods, including use of the TPS algorithm on individual quarters of data. While the KOI list is obviously not yet a complete catalog of every astrophysical transit-like signature in the Kepler field of view, by determining the fraction of KOIs which are detected by TPS we can gain insight into the reliability of the TPS algorithm overall, which has implications for the reliability of TPS detections which are not on the KOI list.

The current list of KOIs contains 1235 planet candidates, plus 498 objects which are either eclipsing binaries (foreground or background) or are a transiting planet on a background object (“false positives”). For the purposes of this analysis, the aggregate of the planet candidate list and the false positive list shall be referred to as the “KOI list.” The list was compiled using the first five quarters of Kepler data, which has two consequences for the current comparison. First, any KOI which has fewer than three transits in the Q1–Q3 interval cannot be detected by TPS; there are 139 such KOIs, which we have excluded from the comparison. Second, the KOI detections will have a more favorable S/N than the Q1–Q3 TPS detections, which will result in some of the latter falling below the detection threshold. No attempt has been made to identify or remove the targets which fall into this category. In addition, TPS returns only the most significant detection in a time series, and so any target which contains more than one KOI must be reduced to a single KOI for the purposes of this comparison. In such cases, it is necessary to determine which KOI on a given target corresponds to the TPS detection, if any. This is accomplished by comparing the period of each KOI on a given target star with the period of the detection, and selecting the KOI which most closely agrees in

[A color version of this figure is available in the online journal.]
period with the detection, taking into account the fact that the TPS period can differ from the KOI period by a rational factor (2, 0.5, 3, 0.333, etc.). Removal of multiple KOIs per target star eliminates 221 KOIs from the comparison, yielding 1373 KOIs which we expect to be potentially detectible within the Q1–Q3 data set.

Out of the 1373 KOIs described above, only 1242 (90.5%) meet both the MES and MES/SES ratio criteria for a detection in TPS. Figure 13 shows the MES and MES/SES ratio for each target star which contains a KOI but which did not meet both the criteria required to be considered as a detection in the Q1–Q3 data set. Due to the aforementioned S/N consideration, it is not a surprise that some KOIs were not detected due to insufficient signal; similarly, the fact that longer flux time series, with more transits, were used in construction of the KOI list makes it inevitable that some KOIs were rejected in the current analysis due to low MES/SES ratio. The remainder of this analysis will be confined to the 1242 target stars which present both a KOI and a detection.

The most straightforward way to determine whether the TPS detections agree with the KOI list is to compare the epochs and periods of the two. More specifically, it is possible to define a period figure of merit, $P_M$, which is the ratio of the KOI period to the TPS period for a given target star; and an epoch figure of merit, $E_M$, which is the difference between the KOI and TPS epochs divided by the KOI period. Figure 14 shows $P_M$: the left plot shows all the values of $P_M$, while the right plot shows the distribution of values clustered around $P_M = 1.0$. Note that the distribution in the right-hand plot is quite narrow, with a standard deviation of $1.10 \times 10^{-4}$. The number of targets for which $P_M$ lies within 0.001 of 0.2, 0.25, 0.333, 0.5, 1.0, 2.0, 3.0, or 4.0 is 1232 out of 1242, or 99.1%.

Figure 15 shows, on the left, all values of $E_M$. The distribution of $E_M$ is not as tight as for $P_M$, as shown in the right-hand

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Figure 10. Illustrated analysis procedure for KIC 2309719, continued. Top: maximum MES as a function of period for detection of transits with 3.5 hr durations. Middle: whitened flux time series, with expected transit times indicated by green, dashed vertical lines. Bottom: whitened flux time series folded at the detection period of 54.36 days, summed into bins of 29.4 minute width, and zoomed on the detection phase.

(A color version of this figure is available in the online journal.)
A total of 23 target stars agree in period between the KOI list and the TPS detections, but not in epoch. In this case, “agreement” can include periods which differ by a rational factor, as described above. Of these, 14 are eclipsing binaries, and their epoch disagreements fall into two categories: in 11 cases, the TPS epoch is for the primary eclipse and the KOI is for the secondary, or vice versa; in three cases, the target has a continuous, near-sinusoidal oscillation at the eclipse period, which can introduce an irresolvable ambiguity in the TPS epoch determination. Of the remaining targets with good period agreement but a discrepancy in epoch, two targets appear to disagree by a time which is very close to one long cadence interval of 29.4 minutes; two targets were “overfolded,” yielding a TPS period which is a fraction of the KOI period (1/2 and 1/3, respectively) and a TPS epoch which is displaced from the KOI epoch by one and two TPS periods, respectively; one target was in transit at the start of observations, causing an edge-effect confusion. The remaining four targets have unexplained offsets in epoch, which are all on the order of two long cadence intervals.

3.2.2. Agreement in Epoch but Not Period

Only one target star agrees in epoch but disagrees in period between the KOI list and the TPS detections. In this case, the TPS and KOI periods are rationally related, but in an unexpected way: the TPS period is 2/3 of the KOI period (0.79815 days versus 1.1973 days, respectively).

3.2.3. Agreement in Neither Period Nor Epoch

A total of nine target stars show disagreement in both period and epoch between the KOI list and the TPS detections. There is no clear unifying feature to their flux time series, but in general they appear to be poorly conditioned: large variations which have been poorly corrected in PDC, significant numbers of negative outlier values, etc. It is likely that all nine of these cases contain artifacts or stellar variations which have been misidentified by TPS, and the fact that these target stars also contain KOIs is due to random chance.

3.2.4. Summary of Comparison

Out of the 1373 KOIs which have three or more transits in the Q1–Q3 Kepler data set, a total of 1209 were correctly detected
Figure 12. Illustrated analysis procedure for KIC 2010191, continued. Top: maximum MES as a function of period for detection of transits with 2.5 hr durations. Middle: whitened flux time series, with expected transit times indicated by green, dashed vertical lines. Bottom: whitened flux time series folded at the detection period of 3.43 days, summed into bins of 29.4 minute width, and zoomed on the detection phase.

(A color version of this figure is available in the online journal.)

Figure 13. MES and MES/SES ratio for target stars which contain a KOI, but do not meet the criteria for a detection in the Q1–Q3 data set. The vertical line indicates the cut on the MES/SES ratio, the horizontal line indicates the cut on the MES value. The upper-right quadrant represents events which pass both cuts and is thus empty.

by TPS, although in a few cases the TPS-detected period is a harmonic or subharmonic of the KOI period, and in some other cases the TPS-detected epoch is similarly displaced relative to the KOI epoch. This represents a correct detection rate of 88.1\%. Of the balance, the largest effect is false negatives—target stars for which no TPS detection was reported. False negatives
account for 131 KOIs, or 9.5% of the KOIs. These cases are believed to be primarily due to the fact that the TPS detections are based upon Q1–Q3 data while the KOI list is based upon Q1–Q5 data; the additional quarters of data approximately double the number of observations, resulting in an expected 40% increase in S/N. An additional 23 targets (1.7%) demonstrated agreement in period but not epoch, though the causes of most of these discrepancies are understood. An additional one target star (0.07%) apparently detected the KOI-specified epoch but not the KOI-specified period nor any harmonic or subharmonic of same. Finally, nine stars (0.7%) reported a TPS detection which does not agree with either the epoch or the period of the corresponding KOI; these cases are thought to be false-positive detections which occurred on KOI targets solely because of random chance.

4. FUTURE PLANS AND OPEN RESEARCH AREAS

The 5392 detected signals in this data set are not expected to include every true positive transiting planet signal, nor are they expected to be free of false-positive signals. Improving the
performance of the TPS algorithms on both of these topics is an active area of development.

The most likely cause of missed signals is the cut on MES/SES. From Figure 13, we can see that there are a number of transiting planet candidates in the KOI catalog with MES/SES below the current threshold of $\sqrt{2}$, which indicates that the hard cut currently in use is causing false negatives in some cases. Additionally, it seems likely that the hard cut is causing false negatives in long-period cases in which only two transits are expected in a given data set. Development effort is focused on finding a means to eliminate this somewhat heuristic cut, which would probably require implementation of a more suitable algorithmic approach that would eliminate the large number of false positives which are currently removed by the MES/SES cut while preserving the smaller number of true positive detections.

One promising candidate for improving both false-positive rejection and true positive retention is implementation of a robust statistic. The current TPS algorithm performs a rather simple combination of SES into an MES. This is a computationally tractable approach, but it means that TPS is not sensitive to cases in which single events of wildly different depth are combined into an MES (i.e., TPS has no means to reject a detection which “does not look like a transit”). The robust statistic approach would follow the initial TPS detection with a robust fit of a periodic square pulse to the light curve. This has the potential to reject detections which do not have the characteristic near-constant depth of a real transit while preserving detections which are currently eliminated by the MES/SES cut.

The Kepler target list includes several thousand eclipsing binary stars. Because of the detailed structure of these light curves, it is difficult for TPS and the downstream automated processing system to function correctly on these; this is most especially the case for contact binaries. As a consequence, it is rarely the case that a system with an eclipsing binary can be searched for a transiting planet as well. In the future, this will be addressed by making use of our existing prior knowledge of the list of eclipsing binary target stars to subject these targets to an additional pre-processing step which removes the eclipsing binary signature and simplifies the task of searching for planets.

At this time, there is no algorithm in the Kepler analysis pipeline which records the presence of single, non-periodic events which are potential transits. In some cases, such single events are potentially interesting in that they may represent a true transiting object for which the second transit has not yet occurred. These signals would potentially serve as an indicator of target stars which are deserving of further scrutiny, as a second transit may occur later in the mission. Even if no such transit occurs, a single deep transit could represent an extrasolar planet with a long period, for which the second transit will not occur during the lifetime of the Kepler spacecraft.

As mentioned above, the TPS algorithm is designed to detect transits which are perfectly periodic, and is capable of detecting transits with small amounts of TTV, albeit with reduced significance. It is likely that transiting planet signals with TTV are being missed, either because the detection statistic is reduced sufficiently by TTV to fall below the TPS threshold, or because the TTVs are so large that no detection can occur. Development of a transit detection algorithm which can accommodate larger TTVs and remains computationally affordable is an active area of research on the Kepler mission.

Finally, in addition to all the projected improvements to TPS itself, all of the other software modules in the Kepler analysis pipeline are also undergoing continual improvement. It is expected that improvements in the CAL, PA, and PDC modules will result in the presentation of higher-quality flux time series to TPS, and a corresponding improvement in planetary detection and false-positive rejection relative to current capabilities.

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Facility: Kepler

APPENDIX

JOINT TIME-FREQUENCY ANALYSIS OF FLUX TIME SERIES

The problem of transit detection can be expressed mathematically as the search of a flux time series, $x(n)$, for a particular signal, $s(n)$, where $x(n)$ contains a non-white, non-stationary, and initially unknown noise spectrum. For the purposes of this discussion, and in the TPS algorithm, $s(n)$ is given by a square pulse of a selected duration, but more complex shapes can also be used.

The first step in the process is to decompose $x(n)$ into its frequency components in a manner which preserves the time variation of the noise. This is done by constructing a digital filter bank, using Daubechies’ 12-tap wavelet (Daubechies 1988); wavelets are used because of their duration-limited nature, which permits preservation of time variation within a selected frequency band. The filter bank is constructed in octaves, such that each output of the filter bank is centered on a frequency which is exactly half that of the next-higher output and exactly twice that of the next-lower output. The output of the filter bank is a set of time series $x_1, x_2 \ldots x_M$, where $x_1$ contains the frequency content of $s$ near the Nyquist frequency, $x_2$ contains the content centered on half of the Nyquist frequency, etc., until $x_M$, which contains the remaining low frequency content of the original flux time series, including the DC term. The same filter bank is used to decompose the signal $s$ into a set of time series $s_i$.

The time-varying noise in each frequency band can be computed from the variance of the $x_i$ time series:

$$\bar{\sigma}_i^2(n) = \frac{1}{2^i K + 1} \sum_{n=2^{-i} K}^{n+2^{i-1} K} x_i^2(k), \quad (A1)$$

where $K$ determines the window over which the variance is computed. The value of $K$ must be chosen such that it is long compared to the typical periods in $x_1$, and also such that it is long compared to the duration of a transit. In practice, TPS uses a value of $K$ which is 30 times the duration of the model transit. Note that, for transits which are small compared to the overall variation of the initial time series, the frequency content of the transit is a small perturbation on the overall frequency content, and so Equation (A1) is valid. For large transits, for example, Jovian planets or eclipsing binaries, the transit itself can distort the estimate in Equation (A1). For this reason, in practice TPS uses a median absolute deviation (MAD) rather than a true variance and scales the MAD by the inverse MAD of a unit-width Gaussian. This gives a value for $\bar{\sigma}_i$ which is not distorted by the presence of large transits, so long as the duty cycle of the transits is small.
With \( x_i \) and \( \hat{s}_i \) time series computed, it is possible to perform pointwise division of the former by the latter. The resulting time series, \( x_i / \hat{s}_i \), is equal to the contribution from the \( i \)th frequency band to white Gaussian noise with unit variance, plus a perturbation from the transit signals (if any are present). In principle, we can now correlate the “whitened” time series \( x_i / \hat{s}_i \) with the time series \( s_i \) to determine the strength of the latter signal in the former time series, and we can combine the resulting correlations to determine the total transit signal as a function of time within the flux time series. However, the pointwise division of the vector \( x_i \) by the noise vector \( \hat{s}_i \) has introduced a time-varying distortion to the shape of the transit, and this distortion must be incorporated into the correlation process by applying the same distortion to the signal vector \( s_i \). By rearranging terms, this can be expressed as a “double whitening” of \( x_i \), which permits us to write an expression for the correlation between \( x_i \) and \( s_i \):

\[
\mathcal{N}_i(n) = \left\{ \frac{x_i}{\sigma_i^2} \ast \hat{s}_i \right\}(n), \quad (A2)
\]

where \( \hat{s}_i \) is the time reversal of \( s_i \), and \( \ast \) represents convolution. \( \mathcal{N}_i \) represents the contribution from frequency band \( i \) to the detection of \( s \) in \( x \). The contributions from all bands can be summed, with appropriate scaling coefficients to take into account the fact that the transform used here is overcomplete (i.e., the number of samples in each \( x_i \) is equal to the number of samples in \( x \), thus the number of samples across all \( x_i \) is \( M \) times as large as the number of samples in \( x \), and this overrepresentation must be corrected). The resulting sum is the contribution from all bands to the detection of \( s \) in \( x \):

\[
\mathcal{N}(n) = \sum_{i=1}^{M} 2^{-\min(i, M-1)} \mathcal{N}_i, \quad (A3)
\]

While Equation (A3) allows the determination of the amplitude of the transit detection as a function of sample number, the significance of this detection can only be determined by comparing that detection amplitude to the detection amplitude which is expected from the noise spectrum. This can be determined in a manner analogous to the detection amplitude, and in the interest of simplicity we simply reproduce the result from Jenkins (2002):

\[
\mathbb{D}(n) = \sum_{i=1}^{M} 2^{-\min(i, M-1)} \left[ \hat{s}_i^{-2} \ast \hat{s}_i^2 \right](n). \quad (A4)
\]

Equation (A4) can be obtained from Equation (A2) by substituting \( \hat{s}_i \) for \( x_i \), and by combining the contributions from individual bands in quadrature, rather than linearly. This corresponds to an intuitive understanding of what it means to estimate the expected detection amplitude from stellar noise sources.

With the definitions above, we can define a time series which represents the detection significance, in \( \sigma \), as a function of sample number. This is obtained by pointwise division of \( \mathbb{N} \) by the square root of \( \mathbb{D} \):

\[
l(n) \equiv \frac{\mathbb{N}(n)}{\sqrt{\mathbb{D}(n)}}. \quad (A5)
\]

The time series \( l(n) \) is the SES time series.

The detection significance of a transit series can be obtained by combining the \( \mathbb{N} \) and \( \mathbb{D} \) values at the locations of the individual transits. The MES for detection of a sequence of transits at widely spaced locations is given by

\[
l \equiv \frac{\sum_{k} \mathbb{N}(k)}{\sqrt{\sum_{k} \mathbb{D}(k)}}, \quad (A6)
\]

where \( k \) runs over the locations of the prospective transits in the time series. In the limit where all of the \( \mathbb{N} \) values are equal to one another, and all of the \( \mathbb{D} \) values are also equal to one another, Equation (A6) reduces to the familiar increase in detection significance as the square root of the number of events.

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