Testing for Stellar Cohabitation in Kepler's Multiple Transiting Planet Systems

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The period-normalized transit duration ratio ($\xi$) can be used as a probe of stellar cohabitation.

The Kepler multiple transiting planet systems (MTPS) are a treasure trove of information for the formation, architecture, and evolution of planetary systems. Although expected to have a low false-positive rate, it is still important to test whether observed transit signals are indeed generated by an MTPS associated with the target star and not an astrophysical false-positive. Using bulk transit properties to perform a false-positive analysis without additional follow-up observations facilitates rapid and uniform studies of MTPSs. A useful parameter that can be derived from the transit properties of a pair of planet candidates is the period-normalized transit duration ratio:

$$\xi \equiv \frac{\text{Inner Transit Duration}}{\text{Outer Transit Duration}} \times \left( \frac{\text{Outer Period}}{\text{Inner Period}} \right)^{1/3}$$

$\xi$ is influenced by orbital geometry and stellar density.

$$\rho^{3/2} \propto \frac{\xi^3}{D} \propto \xi$$

$\xi$ is effectively a ratio of stellar density estimates, modulated by the impact parameters and eccentricities of the candidates. For planets around the same star, $\xi$ is distributed tightly about the mean. For false-positives this distribution can be offset in both scale and location (see Figure 1).

Figure 1: 2-d histograms of the scaled impact parameter ratio as a function of $\xi$ and the stellar density ratio for all Monte Carlo realizations of a synthetic system of two planets each orbiting a different star (i.e. a false MTPS). The color scale is the mean value of points in each bin. All parameters are scaled logarithmically. In the top panel, the stellar components are composed of a Solar-analog star with a coeval binary companion. In the bottom panel the Solar-analog star is paired with a random star from the galactic background. The inner planet has a period of 20.9 days and is always orbiting the Solar-analog, the outer planet has a period of 38.76 days and is always located on the background or companion star. Both planets have circular orbits. As can be seen from the slope in the distribution, the difference in stellar density shifts the peak of the distribution, while the difference in impact parameter sets the extent.

Multiple transiting planet system probability can be estimated via Bayesian Methods.

We performed Monte Carlo simulations of 5,000 candidate pairs in 457 candidate systems. We simulated each pair as an MTPS associated with the reported target star, as an MTPS on background or companion star, and as the following astrophysical false-positives:

- BEB Planet + Background EB
- HEB Planet + Bound EB (Triple Star System)
- BBE Planet + Background Planet
- CPB Planet + Planet (Bound Binary)

We then calculate the probability of each case by invoking Bayes' Theorem:

$$P(j | \xi) = \frac{\pi_j L_j}{\sum \pi_i L_i}$$

$j$ is the case of interest, $n$ is the prior probability of the case in question and $L$ is the likelihood of the observed value of $\xi$ given the modeled case. In our framework, $n$ includes priors on both binary[2] and planet[3] occurrence, galactic backgrounds[4], and the confusion radius of the observed transit signal. $\xi$ includes the probability of the observed $\xi$ value given the model, the transit probability of that case and the fraction of realizations that pass a standard vetting procedure and match the observed transit depth.

The most apparent feature in the MTPS Probability distribution is the large boost in MTPS on a background or bound companion is included. The median MTPS on the target star probability is 0.8% while adding in MTPSs on not the target star increases the median to 1.5%. The primary source of the boost comes from MTPSs on a bound binary companion as they typically have less dilution than comparable background blends. This result suggests some MTPSs may be misclassified from the target, which would have implications for the derived physical parameters of the planets.

Several pairs of multiple transiting planet system candidates are consistent with being astrophysical false-positives.

<table>
<thead>
<tr>
<th>KOI</th>
<th>Planet</th>
<th>Radius</th>
<th>Density</th>
<th>Transit Depth</th>
<th>MTPS on Target</th>
<th>EB</th>
<th>BBE</th>
<th>CPB</th>
<th>$\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>K061.03-K601.01</td>
<td>7.16</td>
<td>0.87</td>
<td>0.73</td>
<td>0.71</td>
<td>1.00</td>
<td>0.85</td>
<td>0.34</td>
<td>0.07</td>
<td>2.16</td>
</tr>
<tr>
<td>K061.03-K601.02</td>
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<td>0.86</td>
<td>0.72</td>
<td>0.71</td>
<td>1.00</td>
<td>0.85</td>
<td>0.34</td>
<td>0.07</td>
<td>2.16</td>
</tr>
</tbody>
</table>

In this table are the ten candidate pairs with the lowest MTPS probabilities, including MTPSs on stars other than the target. These pairs typically have $\xi$ values far from 1 and the dominant false-positive mode is a background EB blend. Most of these KOIs have poor constraints on the confusion radius, which can significantly increase the probability of a background blend. Also note that each pair is considered independent of other pairs in the system and uses only the bulk transit parameters of the KOI catalog. Additional information, such as a better confusion radius from AO or centroiding, or the presence of TVTs can greatly impact these conclusions. Case in point, 377.04 and 377.02 are better known as Kepler-9-b and c.

Conclusions:

- The period-normalized transit duration ratio $\xi$ probes the stellar density of multiple transiting planet system host stars.
- Using $\xi$ we can test MTPS candidates for stellar cohabitation and identify dominant false-positive modes quickly and easily from bulk catalog parameters, which is great for follow-up vetting, and enables uniform studies of MTPSs.
- Most candidates in our sample of 3,007 pairs are consistent with two planets orbiting the same star with a median probability of 0.8% being on the target star and a 0.9% median probability of being on any star in the photometric aperture.