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

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

The *Kepler* multiple transiting planet systems **(MTPS)** are a treasure trove of information on the formation, architecture, and dynamical history of planetary systems. Although expected to have a low false-positive rate[1], it is still important to test whether the observed transit signals are indeed generated by a 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:

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

ξ is influenced by orbital geometry and stellar density.

$$\rho_\star^{1/3} \propto \frac{P^{1/3}}{D} \Rightarrow \xi \propto \frac{\rho_\star f(e_1 \sin\omega_1, e_1 \cos\omega_1, i_1)}{\rho_\star f(e_2 \sin\omega_2, e_2 \cos\omega_2, i_2)}$$

ξ is effectively a ratio of stellar density estimates, modulated by the impact parameters and eccentricities of the candidates. For planets around the same star, ξ is distributed tightly about 1.0. For false-positives this distribution can be offset in both scale and location (see Figure 1).

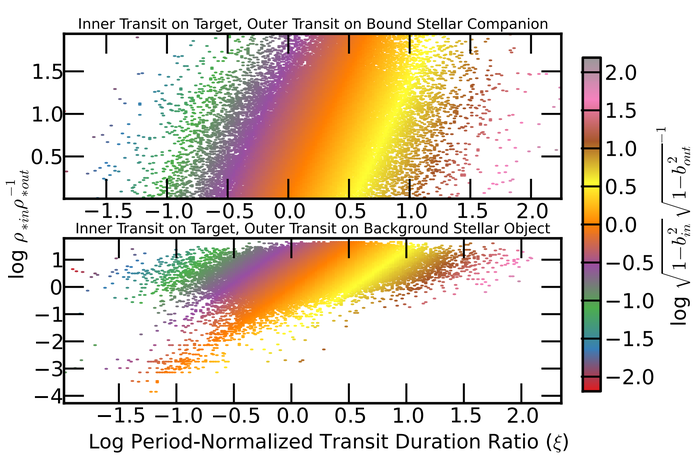

Figure 1: 2-d histograms of the scaled impact parameter ratio as a function of ξ and the stellar density ratio for 1e5 Monte Carlo realizations of a synthetic system of two planets each orbiting a different star (i.e. a false MTPS). The color scale is the mean value of points in each bin. All parameters 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 10.9 days and is always orbiting the Solar-analog, the outer planet has a period of 38.78 days and is always placed on the background or companion star. Both planets have circular orbits. As can be seen from the positive slope in the distribution, **the difference in stellar density shifts the peak of the distribution, while the difference in impact parameter sets the extent.**

References and Acknowledgements

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

We performed Monte Carlo simulations of 1,007 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)
- **BPB** Planet + Background Planet
- **CPB** Planet + Planet (Bound Binary)

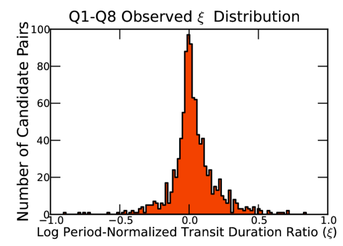


Figure 2: The observed ξ distribution for our Q1-Q8 subsample of 1,007 candidate MTPS pairs.

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

$$P(j \mid \xi) = \frac{\pi_j L_j}{\sum_i \pi_i L_i}$$

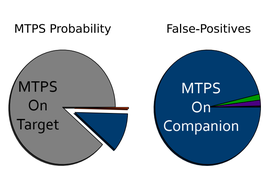
j is the case of interest, π is the prior probability of the case in question and L is the likelihood of the observed value of ξ given the modeled case. In our framework, π includes priors on both binary[2] and planet[3] occurrence, galactic backgrounds[4], and the confusion radius of the observed transit signal. L includes the probability of the observed ξ 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 .

ξ cohabitation analysis also identifies the dominant false-positive modes for each pair of candidates.

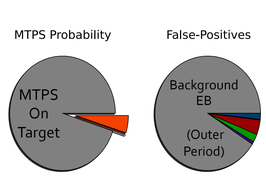
KOI	Period [days]	Radius [Earth rad.]	Depth [ppm]	Transit Duration [hrs]
601.03	1.208	1.49	234.3	1.521
601.01	5.404	2.7	762.9	2.462
601.02	11.679	24.43	1268.2	1.5

Example: KOI-601

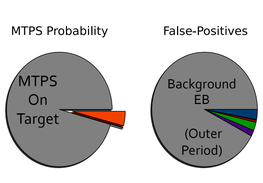
KOI-601 is a 0.972 Solar radius star with a 3-planet candidate system. We applied our analysis to each permutation of candidate pairs in the system from the Q1-Q8 catalog[5].



K601.03:K601.01
ξ = 1.02
MTPS on Target Probability = 0.89
dominant false-positive is a MTPS on bound binary companion star (P=0.11).



K601.03:K601.02
ξ = 2.16
MTPS on Target Probability = 0.95
dominant false-positive is 601.02 as a background EB blend (P=0.05).



K601.01:K601.02
ξ = 2.12
MTPS on Target Probability = 0.96
dominant false-positive is 601.02 as a background EB blend (P=0.04).

Although each pair in the system has a relatively high probability of being a MTPS, 601.02 does show a significant probability of being an background EB. This is consistent with the large radius (24.4 Earth radii) and grazing impact parameter (1.03) reported in the catalog.

Most multiple transiting planet system candidates are likely to be MTPSs, but perhaps on a different star.

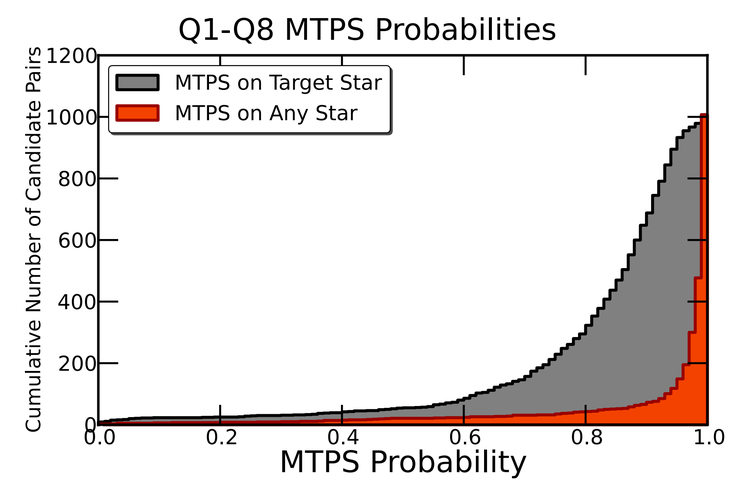


Figure 3: Cumulative distribution of individual multiple transiting planet system probabilities for each candidate pair in our sample of 1,007 pairs. The gray histogram is MTPS on the target star, the orange histogram is total probability of the pair being a MTPS on any star in the aperture.

The most apparent feature in the MTPS Probability distribution is the large boost when MTPSs on a background or bound companion are included. The median MTPS on the target star probability is 0.87 while adding in MTPSs not on the target star increases the median probability to 0.99. 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 results suggest some MTPS KOIs may be 'misplaced' 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.

Ten Worst Candidate Pairs

Inner KOI	Outer KOI	MTPS On Tar.	MTPS Any	False-Positive Total	BEB	HEB	BPB	CPB	ξ
2671.02	2671.01	2.4E-04	3.1E-04	1.00	**1.00**	1.5E-04	5.8E-07	3.7E-07	0.86
505.01	505.06	2.0E-03	3.4E-03	1.00	**1.00**	7.1E-06	3.5E-04	3.7E-06	0.31
2339.01	2339.02	0.02	0.03	0.97	**0.52**	9.1E-08	0.34	0.11	0.48
1747.02	1747.01	7.0E-04	0.03	0.97	3.0E-05	9.2E-06	**0.97**	7.2E-06	4.65
191.02	191.01	0.04	0.04	0.96	**0.91**	0.05	4.6E-07	1.0E-04	0.89
377.01*	377.02*	0.09	0.09	0.91	**0.91**	1.1E-05	8.5E-06	7.9E-06	1.12
159.02	159.01	0.04	0.13	0.87	**0.69**	1.4E-05	0.05	0.14	0.50
1806.01	1806.03	0.19	0.20	0.80	**0.69**	6.1E-05	0.04	0.07	2.16
115.03	115.01	0.25	0.27	0.73	1.8E-05	1.8E-05	**0.73**	1.3E-03	1.28
1831.02	1831.04	0.26	0.30	0.70	**0.63**	0.06	6.2E-03	2.0E-03	5.11

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 ξ 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 TTVs can greatly impact these conclusions. Case in point, 377.01 and 377.02 are better known as Kepler-9 b and c!

Conclusions:

- **The period-normalized transit duration ratio ξ probes the stellar density of multiple transiting planet system host stars.**
- **Using ξ 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 1,007 pairs are consistent with two planets orbiting the same star with a median probability of 0.87 of being on the target star and a 0.99 median probability of being on any star in the photometric aperture.**