15 Candidate Non-Transiting Giant Planets in the *Kepler* Sample

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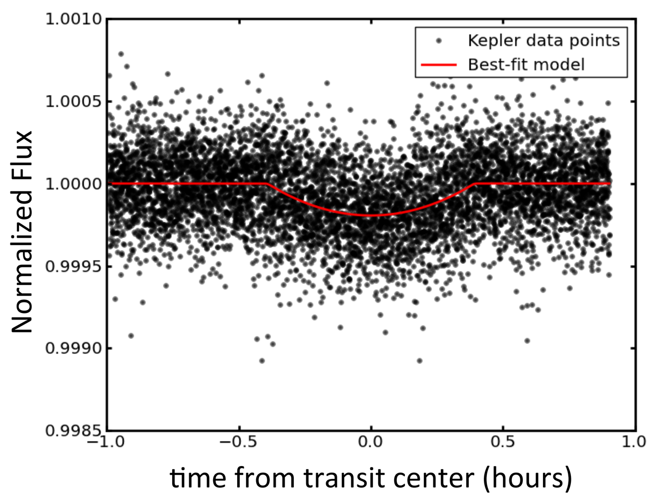
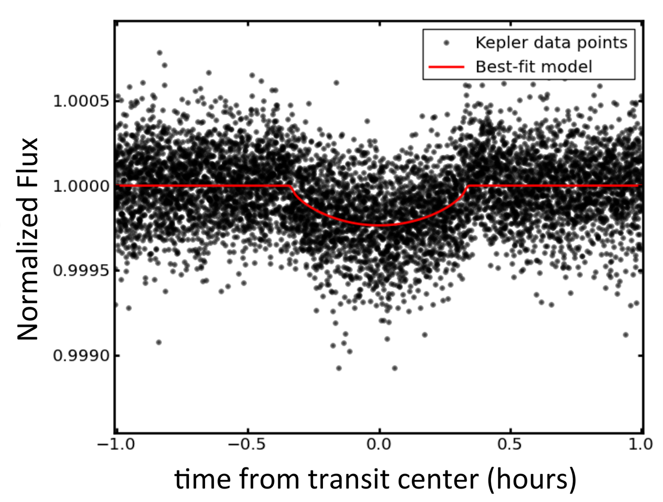
Abstract The high precision, continuous time coverage and long baseline of the Kepler mission have allowed for the first analyses of transit timing variations (TTVs) induced by dynamical interactions between planets. Nearly all previous TTV studies have focused on the detection, characterization, and validation of planetary systems in near-resonant configurations. Transit timing data also contains potentially useful information about the existence of massive, non-resonant companions (Borkovits et al. 2002). We have begun a new study to search for such companions. Here, we present preliminary results from our analysis of the first 16 quarters of Kepler data and discuss the implications for the presence of massive, non-transiting companions in these systems.

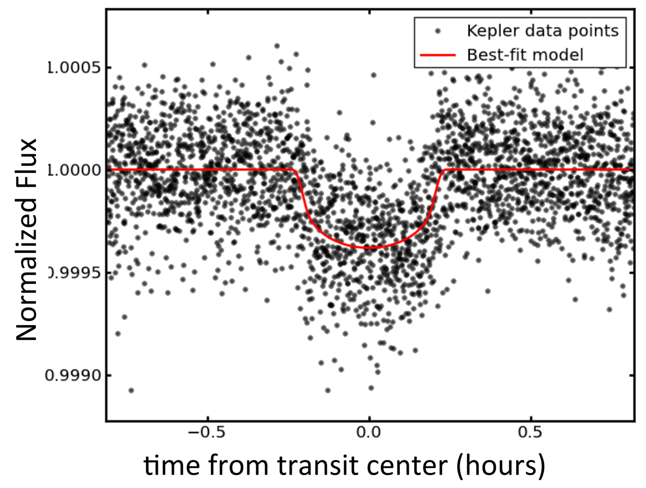
Fitting the transits To find accurate TTVs, it is important to have accurate transit fit parameters. In system with TTVs, initial transit fits can be misleading, as the TTVs lead to increased time-wise scatter (in phase folded space) between individual transits. To avoid this, we utilize an iterative fitting process. The initial raw transit fit serves as a template, which is used to generate preliminary TTVs. Then, this process is iterated with re-folded light curves and re-fit transits until best-fit transit parameters remain stable between successive iterations.

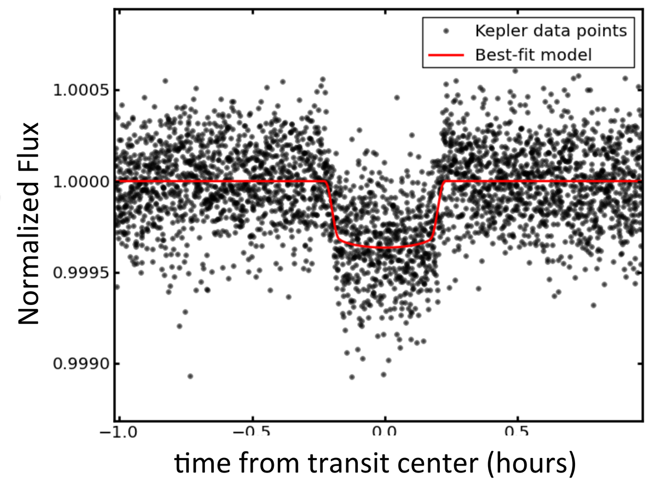




Figures 1, 3, above, below: raw transit fit, fit with light curve folded over Kepler period.

Figures 2, 4, above, below: final iterated fit, where light curve has been re-folded over transit timing variations.





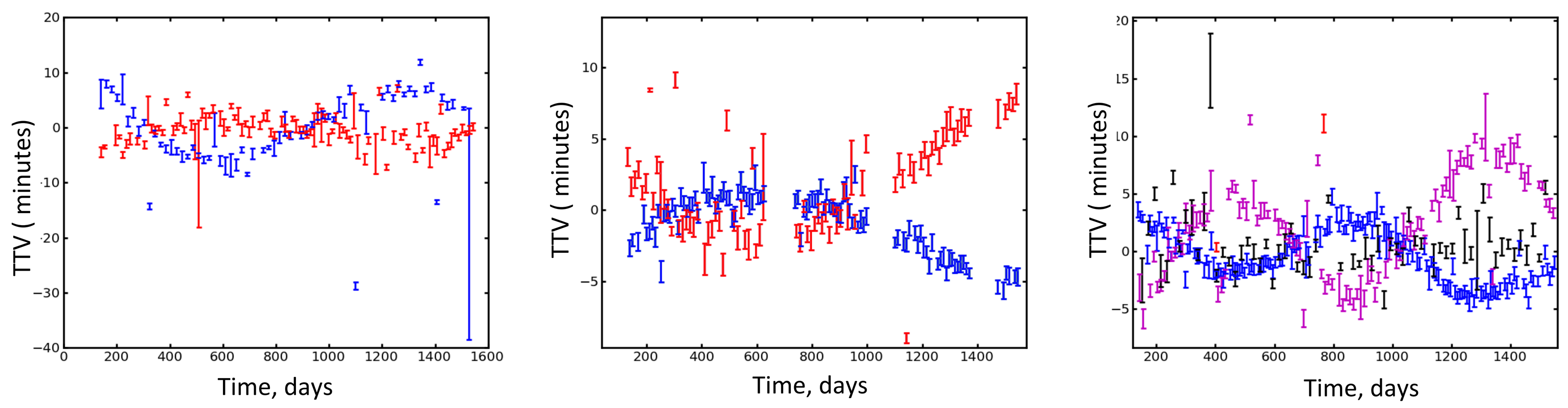


Figure 5: Anti-correlated transit timing variations in various Kepler multi-transiting systems as fit using this algorithm. Anti-correlated TTVs indicate that the bodies are dynamically interacting with each other, and give insight on the mass and other orbital parameters of the bodies.

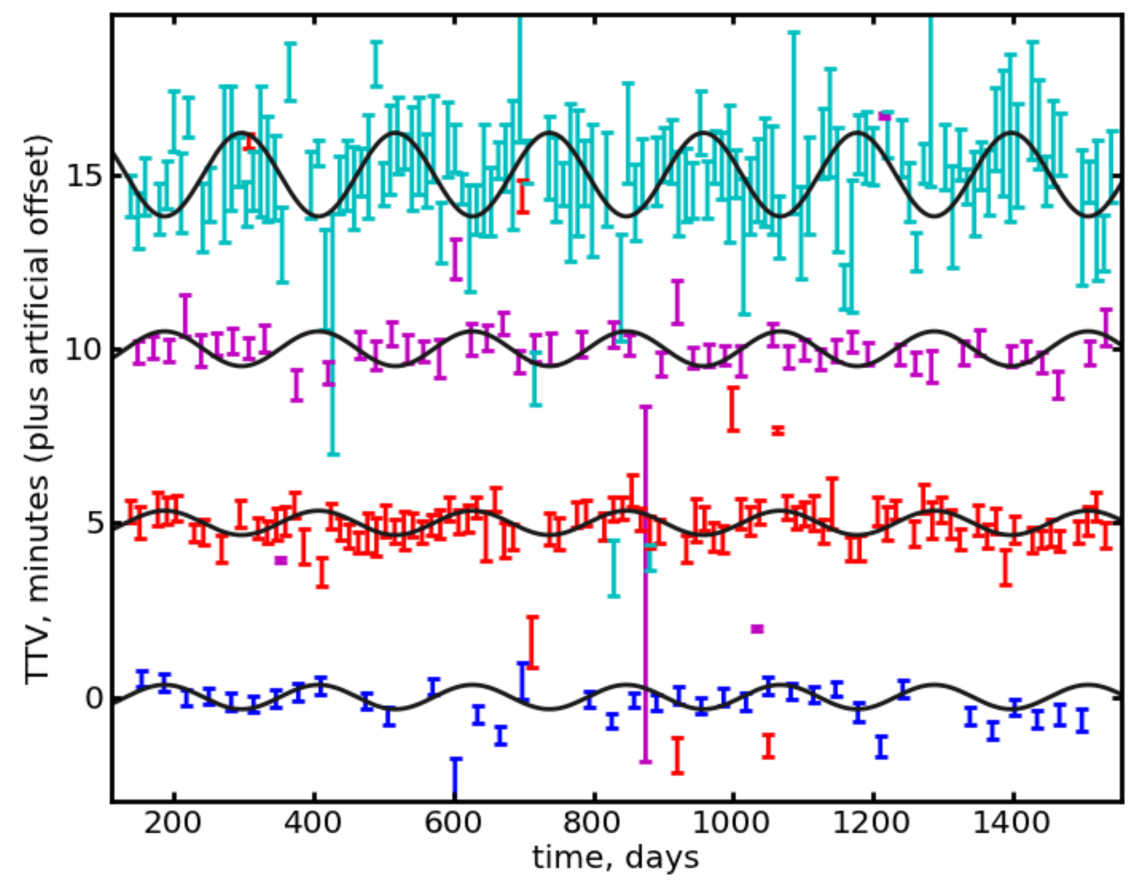


Figure 6: Preliminary MCMC fits of a sinusoidal fit to one of out candidate systems. Initial parameters for the fit were determined by a periodigram and time series statistics. The strongest signals in the system are plotted to the left. Artificial offsets separate the time series. A common period and phase between TTVs of different bodies can imply a perturber in the system.

Candidate Determination Out of all the Kepler multi-planet transiting systems, only a subset will be appropriate to use in an survey of non-resonant companions. To determine the size and contents of this distribution, we used a Lomb-Scargle periodigram to determine significant periods in each of the several thousand TTV time series generated using our iterative method (described to the left). Using statistically significant periods as a starting point, we then performed MCMC fits to quantify the magnitude of transit timing variations following the form:

$$\mathrm{TTV_i} = \mathrm{A_i}\sin\left(\frac{2\pi \mathrm{t}}{\mathrm{P}}+\phi\right)+\epsilon_\mathrm{i}$$

when A_i is amplitude in hours of the i^{th} companion, P is period in days, t is time in days, ϕ is phase, and ϵ_i is vertical offset in hours of the i^{th} companion to each TTV time series. This yielded model parameter and errors on those parameters. When the amplitude for multiple bodies in the system was more than three sigma away from 0 (no signal), we flagged that system as a potential candidate.

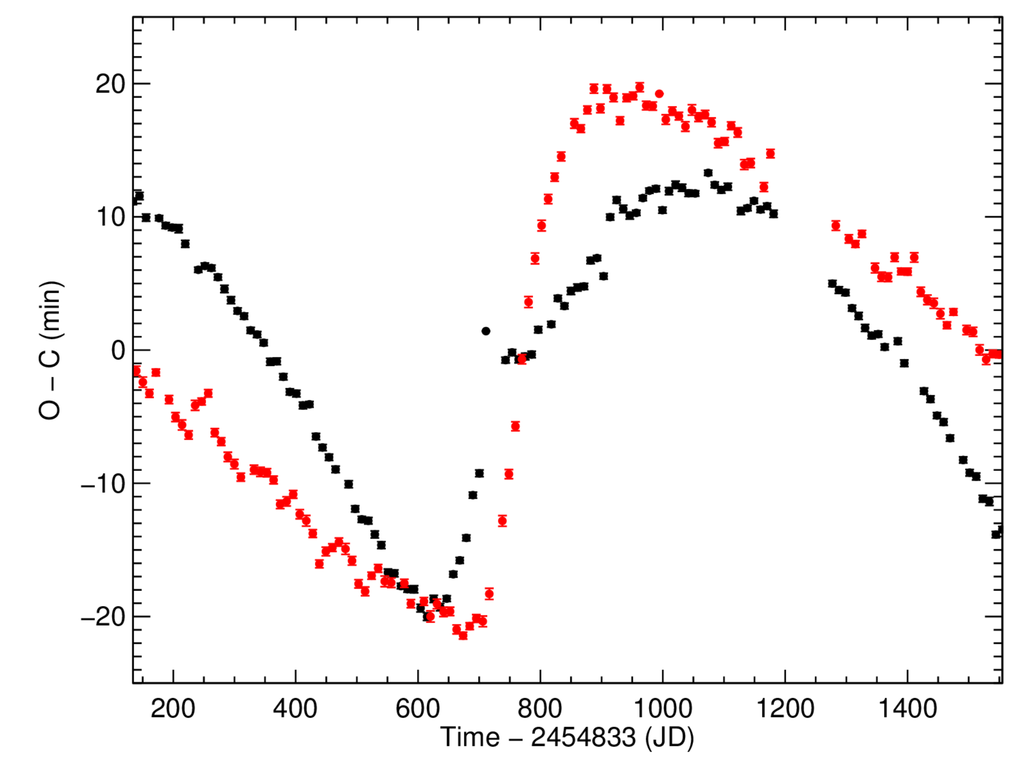


Figure 7: Correlated eclipse timing variations in a Kepler M-dwarf hierarchical triple. Data courtesy Jon Swift. This is an example of the target effect this survey seeks to identify. This effect could potentially be observable for some non-transiting Jupiter-mass planets at 1 AU.

Further Work Since candidates have been generated, the next step for this work is to analyze these candidate systems. This will be done with more refined fitting using analytic formulation derived by Borkovits et al (2011). These refined fitting techniques will allow us to better quantify what exactly we see in our sample. Subsequent numeric simulations will allow us to determine what we would expect to be detectable in this sample, allowing for a calculation of the occurrence rate of Jupiter-mass planets at approximately 1 AU in these kinds of multi-transiting systems. We also intend to collect RV follow-up of our most promising systems to confirm and characterize potential companions.

References

Borkovits, T., et al, 2003, A&A, 398, 1091

Borkovits, T., Csizmadia, Sz., Forgacs-Dajka, E. and Hegedus, T., 2011, A&A 528, 53