Searching for Extreme TTV Planets with QATS

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I. Introduction

Many *Kepler* planets exhibit transits that deviate from a strict Keplerian periodicity; these transit timing variations (TTVs) are caused by dynamical interactions with other planets in the system, resulting in individual transits occurring slightly before or after the Keplerian prediction.

Because most transit searches (including the *Kepler* pipeline) rely on a periodic signal, large TTVs can cause a planet to be missed. Carter and Agol (2013) developed a Quasi-periodic Automated Transit Search (QATS) that accounts for these deviations and allows for strongly interacting systems to be discovered.

I have been fine-tuning QATS to optimize its sensitivity to small planets with extreme TTVs. Here I present the preliminary results of a QATS run on 83% of the KOI systems.

Using QATS we found 18 potential new planets not on the KOI list, some with modest to large TTVs. Many of these candidates are found at or near a resonance with a known KOI, supporting their validity.

II. Method

We have modified QATS to search over a $\Delta\chi^2$ spectrum instead of raw fluxes. For every cadence in the (SAP) light curve, we compute the $\Delta\chi^2$ between a local polynomial fit and a polynomial plus box transit of fixed depth and duration. The box transit model will be a worse fit and produce a negative $\Delta\chi^2$ except at transit cadences. QATS scans this $\Delta\chi^2$ light curve and identifies the cadences that maximize the total $\Delta\chi^2$ signal within our specified quasi-periodic window. We repeat this for a grid of potential transit depths and durations.

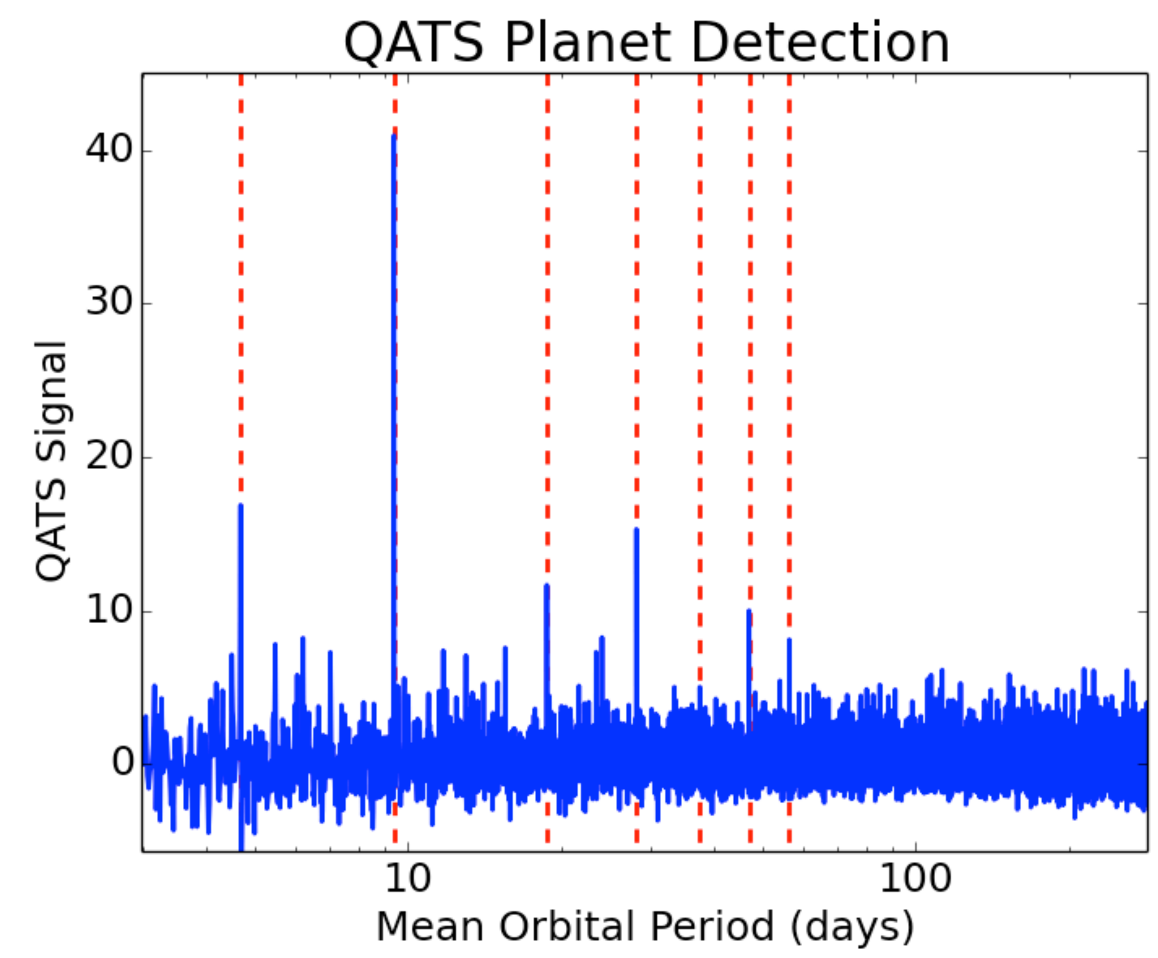
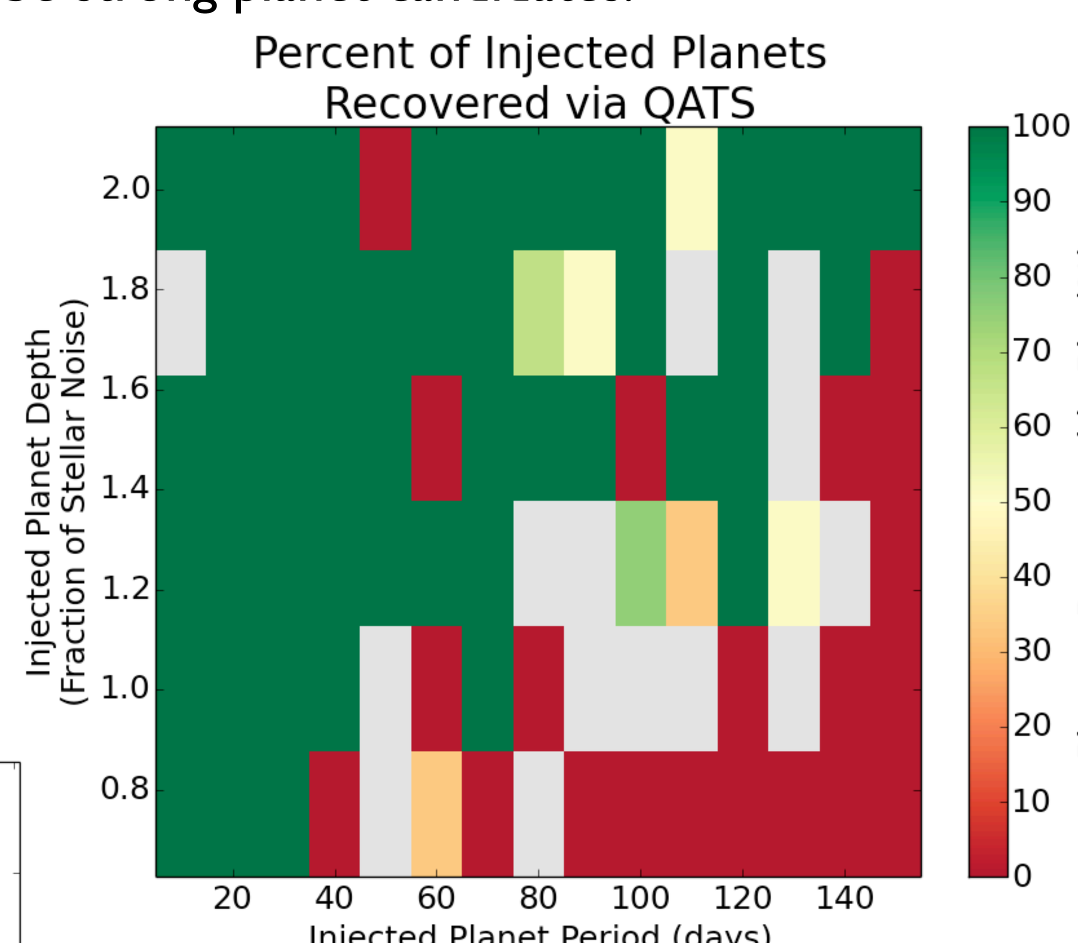


Figure 1: Typical output from QATS for a 9.4 day planet. Planets will produce a significant spike in the signal at their orbital period. Strong sidebands at aliases of the period (dashed red lines) are also indicative of a true planet.

III. Testing via Planet Injection

To ensure our method works as expected, we inject transits into real *Kepler* light curves. Using these injection results, we are able to estimate QATS's false positive rate as a function of a potential planet's period, transit depth, and TTV magnitude. From this, we set a conservative threshold for our search, above which most events should be strong planet candidates.

Figure 2: Our injection recovery rate as a function of injected planet period and transit depth. Due to time constraints until this conference, this was a small sample (150 injections spread over 105 bins; gray indicates no injections fell in that bin). However, the expected trend emerges that long-period, small planets are most difficult to detect, yet we are sensitive to small planets with P < 50 days.



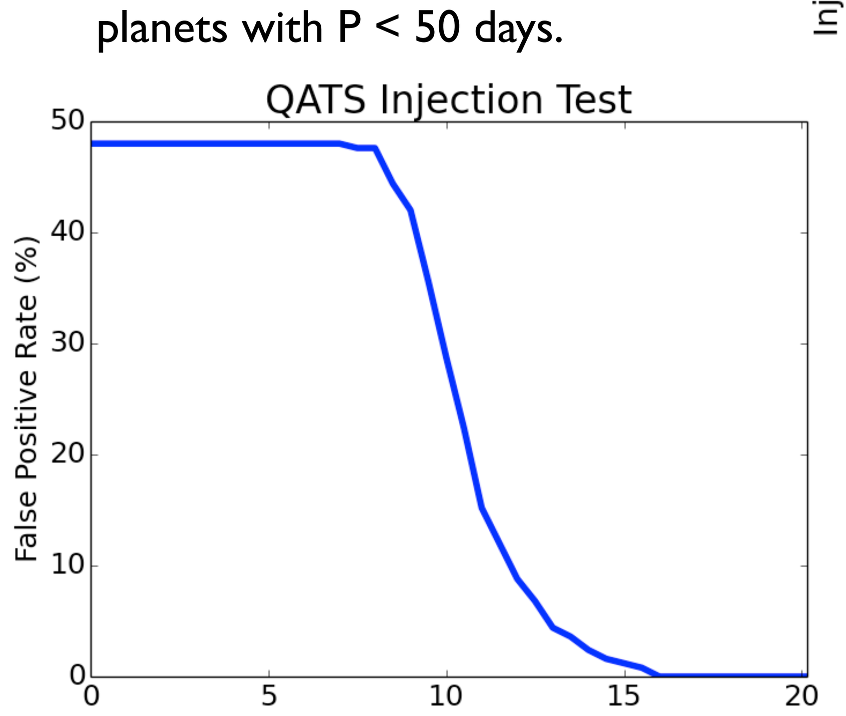


Figure 3: The QATS false positive rate as a function of our cutoff threshold. For this KOI search we chose a conservative cutoff of 18. Most of our detections should therefore be real, but previously overlooked planets.

IV. Preliminary Results

After masking out the known planets, we applied QATS to 83% (2990) of the KOIs. **We found 18 candidate planets not currently on the KOI list (to our knowledge, 6 are completely novel)**, many of which exhibit TTVs and have a period near resonance with one of the known KOIs in the system.

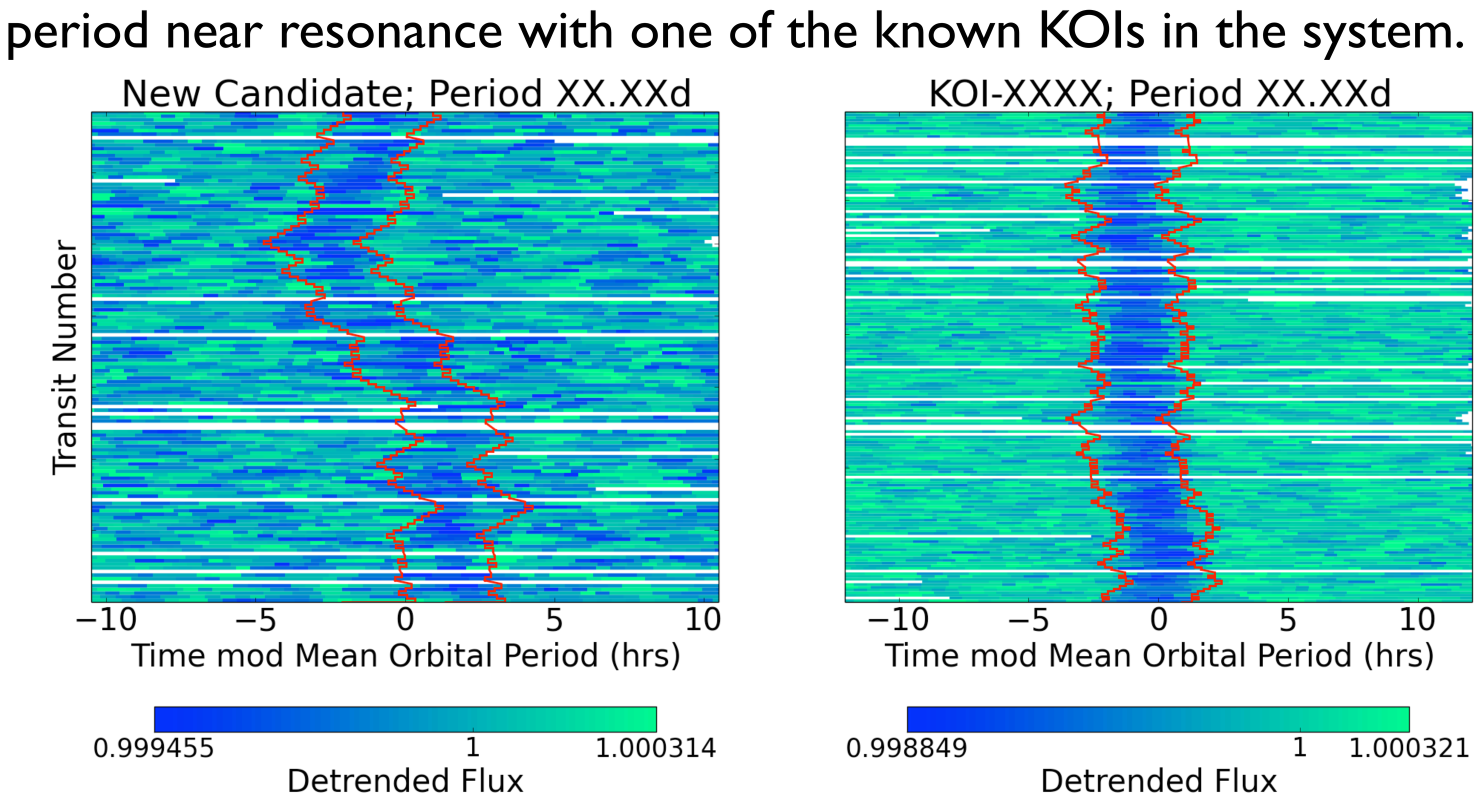


Figure 4: River plot for one of our new candidates with its known KOI. Each row shows the detrended transit fluxes folded on the mean period, (O-C) with the start and end of transit (as identified by QATS) marked as red bars. A perfectly periodic planet would present a vertical blue stripe centered at 0, while this candidate's winding, river-like structure is due to TTVs. The period ratio between these planets is 1.334, almost perfectly 4:3.

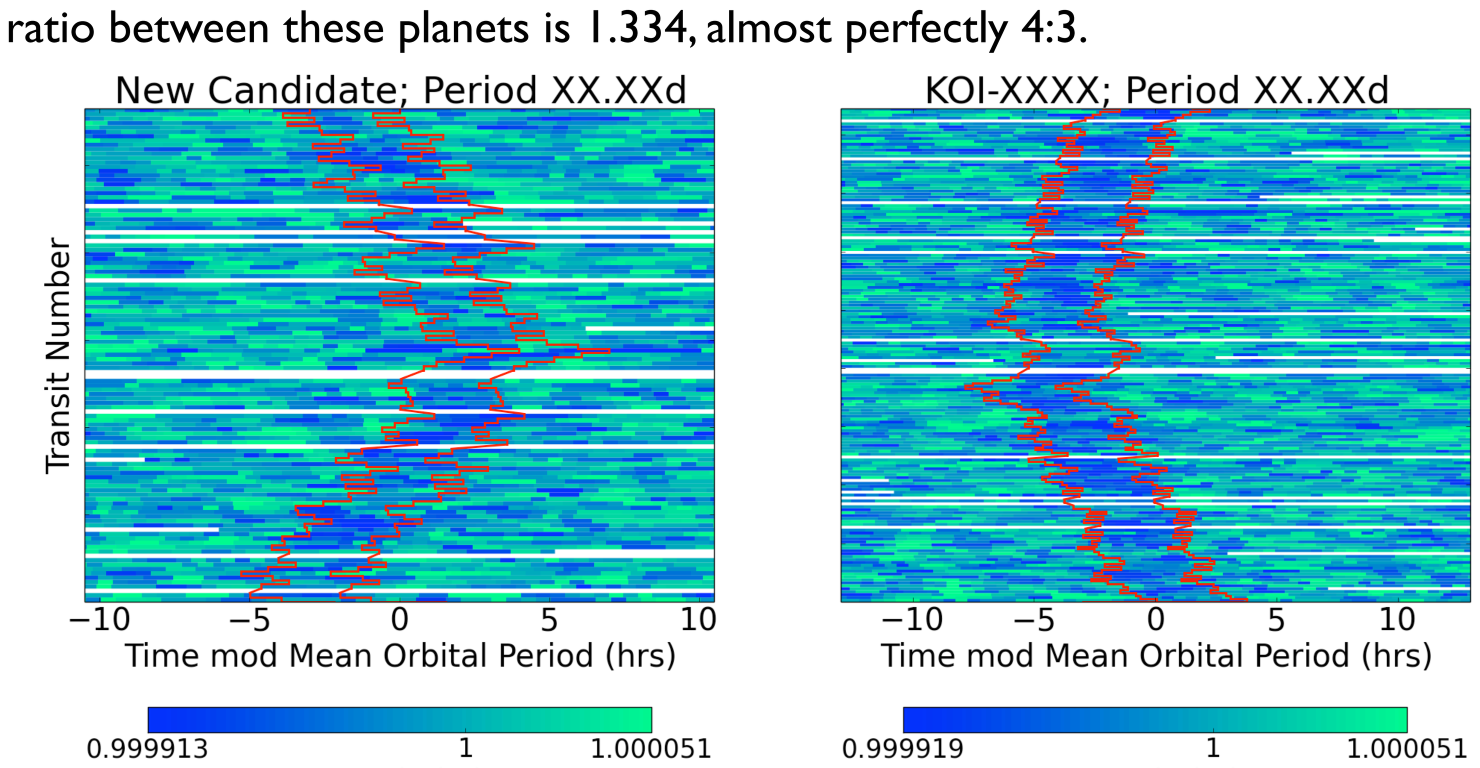


Figure 5: River plot for another of our candidates with its known KOI. These planets have a period ratio of 1.5002, right at the 3:2 resonance.

V. Future Plans

- Characterize, model, and confirm our new planet candidates
- Search the *Kepler* stars without any KOIs to look for mutually interacting, extreme TTV planets missed by the pipeline
- Tweak the QATS pipeline to handle current issues with short-period stellar variability to allow a search over the ~17% of stars currently excluded
- Apply a modified QATS routine to the eclipsing binaries to search for circumbinary planets

Contact Info and Acknowledgments

If you'd like more details about our method or results, please come find me or contact me at eakruse@uw.edu.

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