A survey for very short period planets in the *Kepler* data

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The Big Question

Are there exoplanets in very short-period (only a few hours) orbits, even perhaps all the way down to the stellar surface?

Introduction & Motivations

Tidal interactions between close-in planets and their host stars can influence the planetary orbits, and considerations of the total angular momenta for hot Jupiter systems (Jackson et al., 2009; Levrard et al., 2009) show that the vast majority are unstable against tidal decay. Moreover, if they exist (we'll find out they do at this meeting), rocky planets with orbital periods of a few hours would induce measurable stellar radial velocity (RV) signals (Figure 1). Such planets would provide the easiest (even maybe, currently the only) opportunity to estimate masses for rocky exoplanets. With these motivations, we looked for very short-period planets using *Kepler* data.

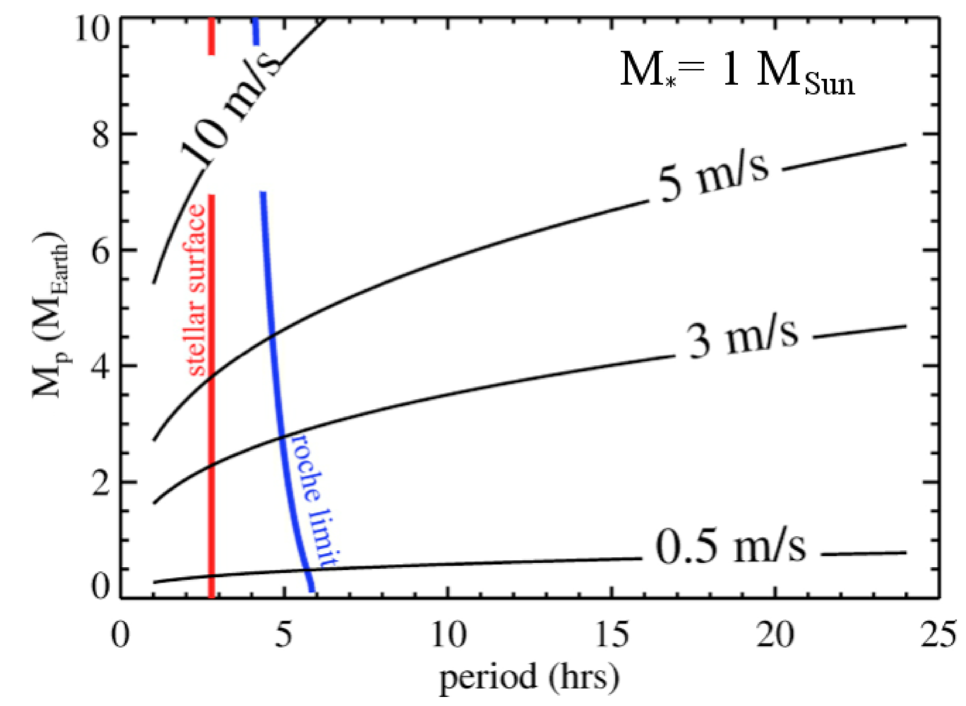

Figure 1: Stellar radial velocities (RVs) induced by planets with orbital planes aligned with our line of sight to the system for a range of masses (M_p) and orbital periods. The stellar mass $M_\star$ is 1 M_{Sun}.

The Transit Search

Using all available Q0-11, long-cadence *Kepler* data, we looked for transits with periods $P < 12$ hours as follows:

1. **We subtracted/divided all quarter's data by that quarter's mean value and then applied a mean boxcar filter of width 0.5 days.**
2. **We applied the EEBLS algorithm (Kovács et al., 2002) for $2 <$ hours $P < 12$ hours.**
3. **We retained candidates meeting a few selection criteria, including a signal-to-noise ratio $SNR > 3$ (Jackson et al., 2013).**

The Transit Search (cont.)

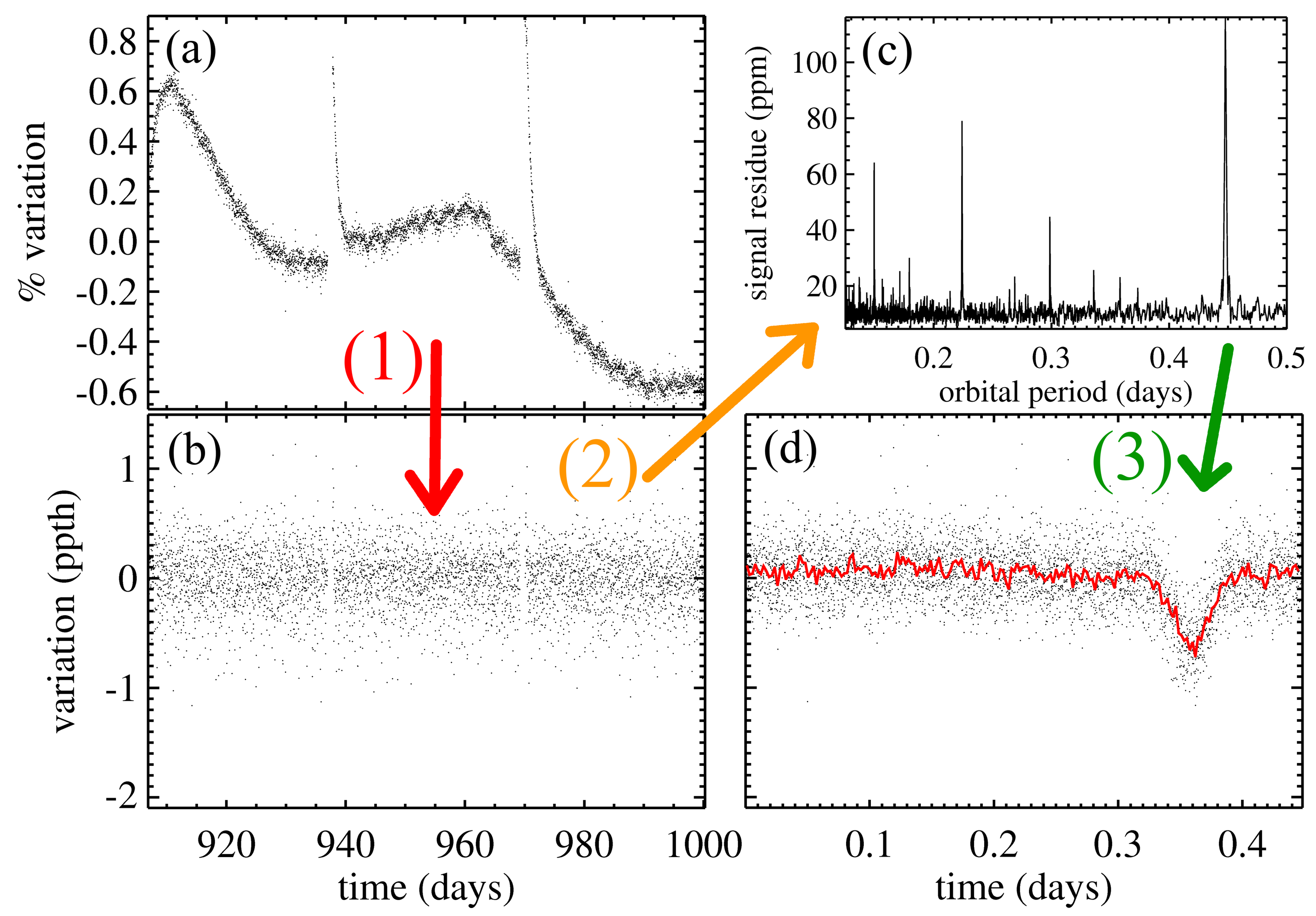

Figure 2: (a) Raw *Kepler* data for the KIC 10453521 candidate planetary system with variations measured in parts-per-thousand (ppth). (b) Detrended data in parts-per-thousand ppth. (c) EEBLS spectrum, with a peak at about 0.44 days (≈ 11 hours). (d) Data from (b) folded on that 11-hour period. The red line shows the binned data.

Weeding Out False Positives

After tossing reported (Slawson et al., 2011) or likely eclipsing binary candidates, we looked for > 3-σ in-transit photocenter shifts among the remaining candidates. Batalha et al. (2010) found that such a shift may indicate the transit signal is distorted and the transiter may not be a planet after all. After winnowing our list thusly, we had four candidates, two (Kepler-78 b – Sanchis-Ojeda et al., 2013 and KOI-1843.01 – Ofir & Dreizler, 2013; Rappaport et al., 2013) were reported previously and two (orbiting KIC 7269881 and 10453521) were not. (*The photocenter analysis code in our original manuscript contained a bug that incorrectly gave us more candidates, but we have now corrected it.*)

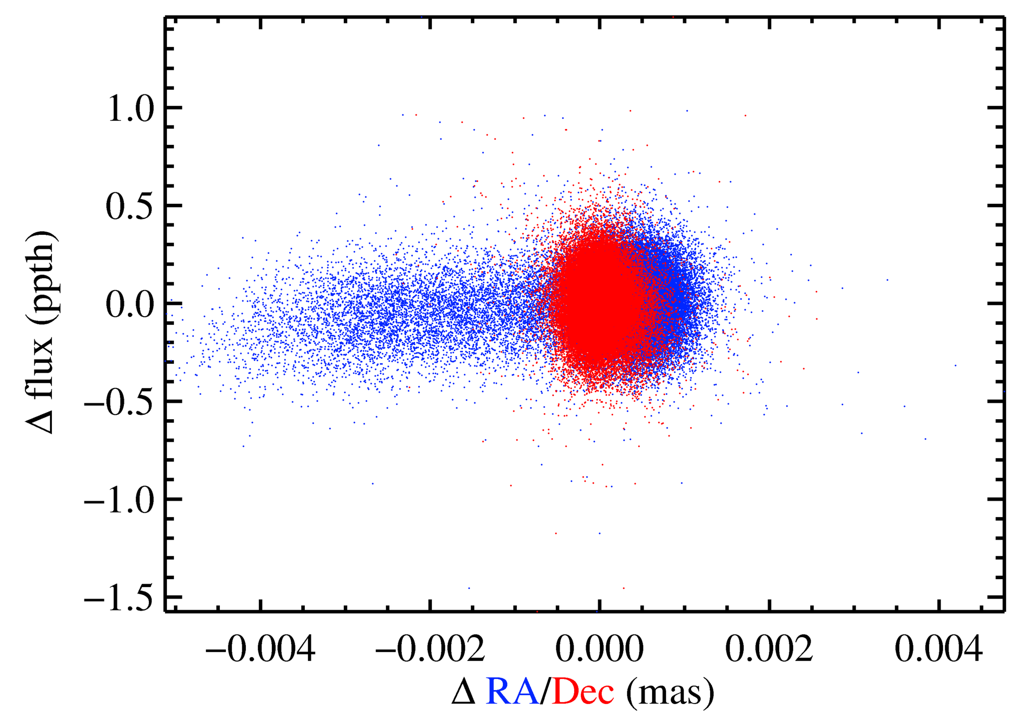

Figure 3: Flux variations Δ flux vs. photocenter variations (milliarcsecs mas) for KIC 12023078. Blue/red points indicate RA/Dec. There is a clear photocenter shift correlated with flux variations, suggesting the transit is distorted.

Photometric Modeling

For these four candidates, we applied a full photometric model, including the transit and eclipse, among other signals, and using a combination of Levenberg-Marquardt and Markov-Chain Monte-Carlo algorithms to account for non-Gaussian noise. These model fits are shown in Figure 4, and the fit parameters can be found in Jackson et al. (2013) – pre-prints available. Only in the case of the planet orbiting KIC 8435766 (Kepler-78 b) do we robustly detect an eclipse; in the other cases, the nominal fits are consistent with no eclipse (at 3-σ).

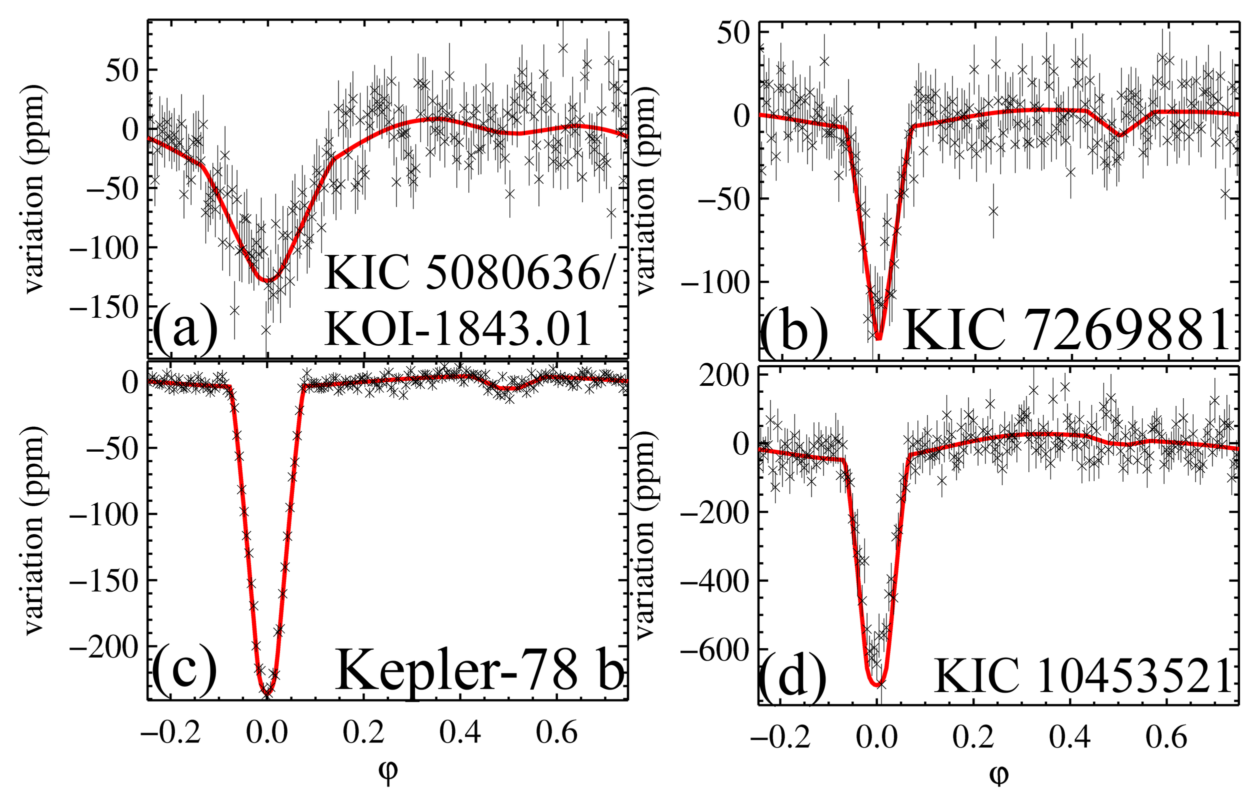

Figure 4: Photometric data (X's) and model fits (red lines).

Implications

Where do these objects come from? The usual origin scenarios for close-in planets may not apply to these candidates. For example, many close-in planets may originate through planet-planet scattering/Kozai resonances + tidal interactions (Rasio & Ford, 1996; Weidenschilling & Marzari, 1996; Fabrycky & Tremaine, 2007). In this scenario, the pericenter of the original, highly eccentric orbit is half the semi-major axis a of the final orbit (Ford & Rasio, 2006). However, Figure 5 shows that, for Earth-like densities, the planets would have been disrupted at half the current a-values. Another possible origin is as the remnants of disrupted gas giants: here, the candidates began as hot Jupiters, and then tidal interactions brought them through the hot Jupiter Roche limit, disrupting them along the way. However, this scenario requires that tidal decay operates quickly enough to disrupt the progenitors but then slowly enough that we have time to observe the remnants.

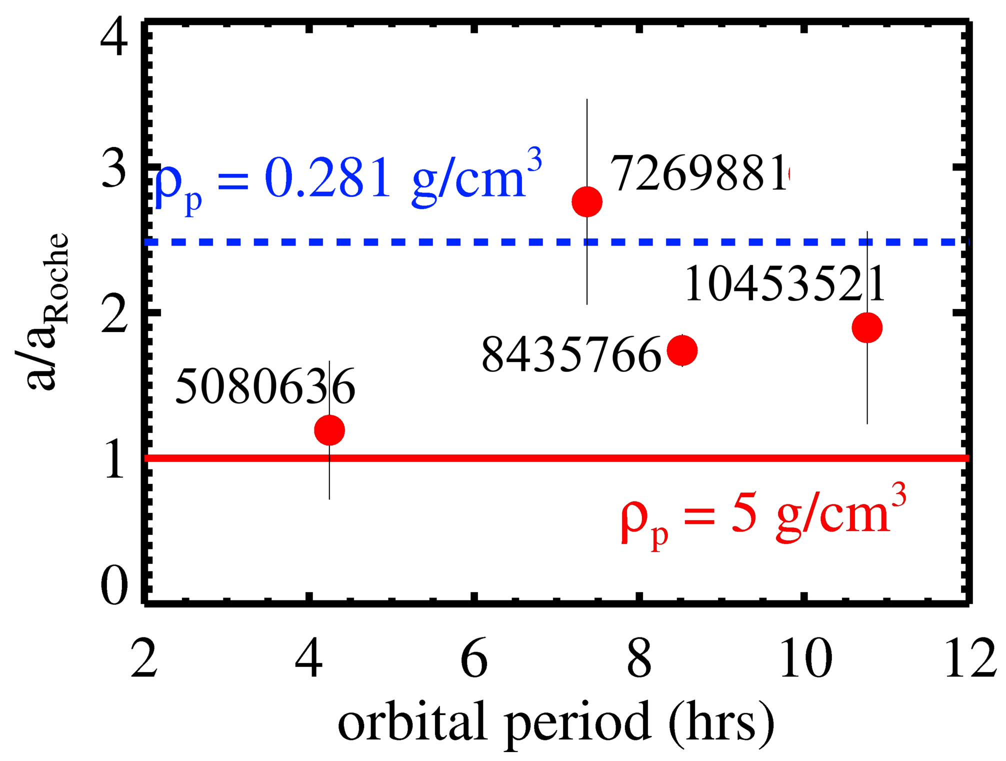

Figure 5: The semi-major axis a divided by the Roche limit a_{Roche}. Red circles show this ratio for the candidates for an Earth-like density of $\rho_p = 5$ g/cm^3, while the dashed blue line shows where $a/a_{Roche} = 1$ if all the planets had the density of a hot Jupiter, 0.281 g/cm^3.

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