Three-Dimensional Orbital Architectures and Detectability of Adjacent Companions to Hot Jupiters

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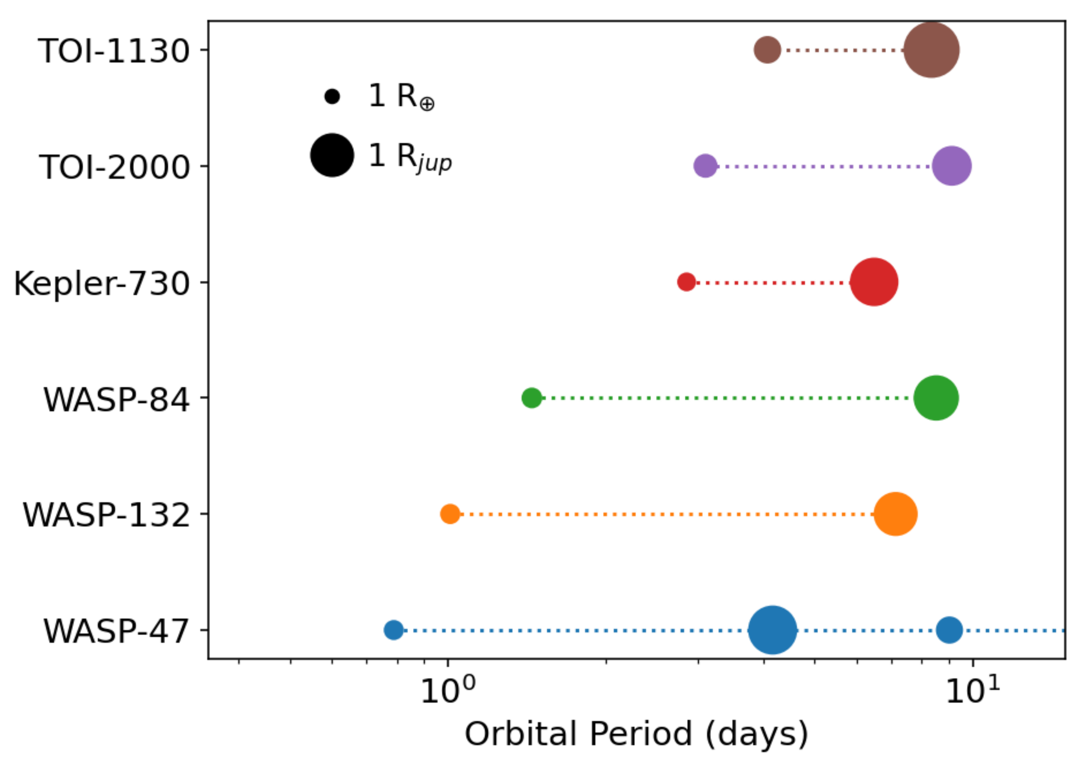
Planetary Formation and Evolution

The puzzle of planet formation and the processes that mediate the assembly of exoplanetary system architectures remains a largely open question. Our ability to classify mechanisms in planet formation has substantially increased in the recent decades as the Kepler, K2, and TESS missions have provided thousands of exoplanet systems (Borucki et al. 2010; Howell et al. 2014; Ricker et al. 2015), no two identical and each the result of a different superposition of formation pathways. Some of these companions are ultra-short-period planets (USP planets; defined as those with orbital period of less than a day or so).



Interestingly, while only one known system with a hot Jupiter detected (WASP-47) hosts an adjacent nearby exterior companion, all known systems with hot Jupiters and nearby companions feature inner short-period companions (see Figure 1). However, this is limited by our ability to detect the companions. The inner companions to hot Jupiters, which are Ultra-Short Period (USP) planets, constitute about 0.5% of all planets (Sanchis-Ojeda et al. 2014); though likely a larger fraction in tightly-packed, multi-planet systems (Adams et al. 2021), are situated in regions where stellar dynamics, particularly the slow stellar spin down observed as stars age, can significantly influence their orbits (Li et al. 2020), (Becker et al. 2020), (Brefka 2021), (Chen et al. 2022).

Figure 1 (left): Orbital Architectures of all known hot Jupiter systems with detected nearby companions.

Methods

We simulate model hot Jupiter systems using orbital parameters corresponding to the currently observed "true" systems, with changes to the initial spatial arrangement, and therefore orbital periods. Integrating over the course of the star's evolution, we capture the approximate resultant states of the model systems. We use *Rebound*'s "ias15" integrator (Rein, Spiegel 2015) with *Reboundx* GR effects and gravitational harmonics package to account for the stellar obliquity (Tamayo, et al. 2020) in 10^5 year integrations (a timescale deemed faithful to the effects of the stellar evolution by testing on longer timescales) for each model system, across which J_2 is logarithmically varied to approximate the stellar evolution. We compare dynamical results to secular theory predictions.

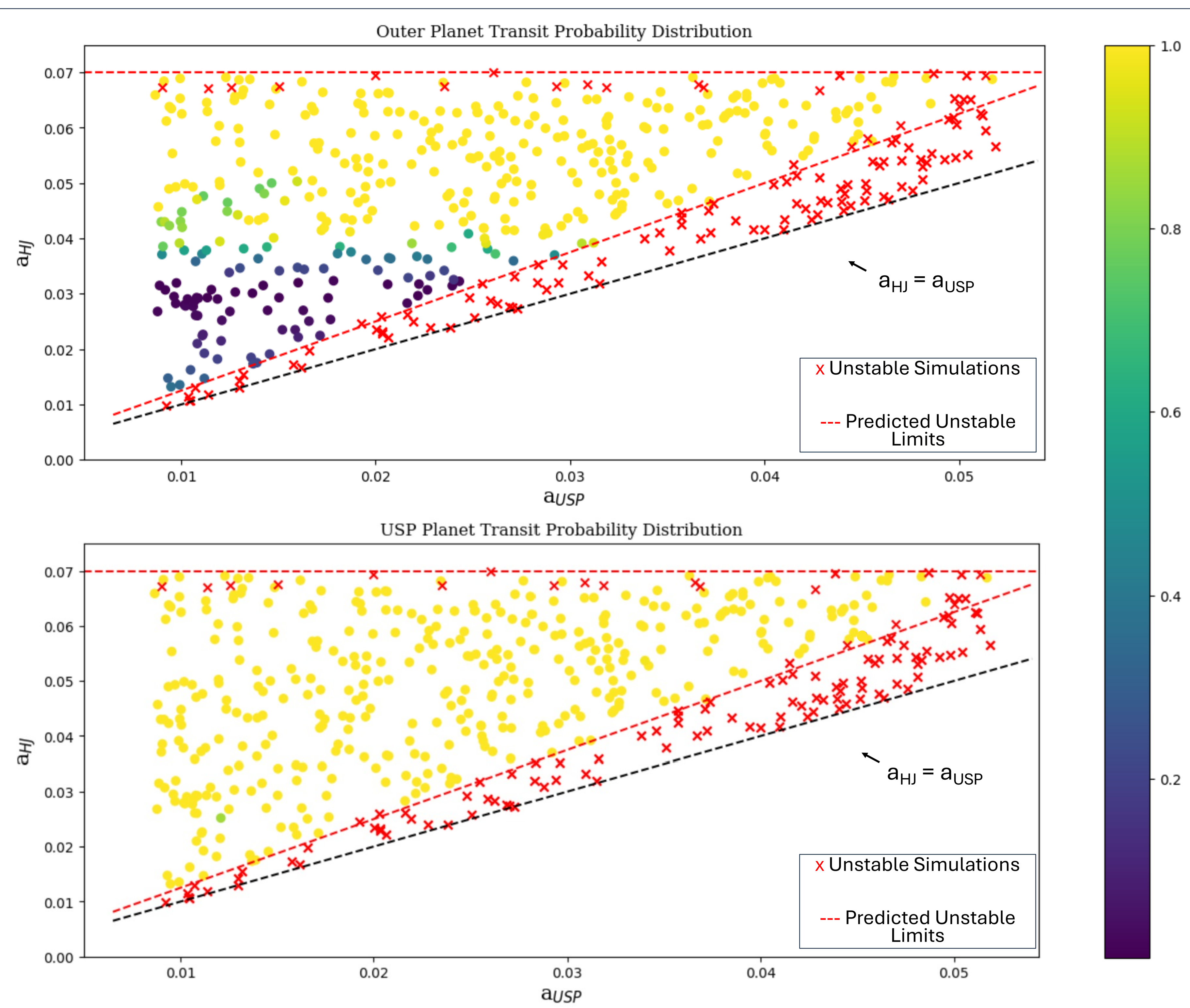


Figure 2 (above): We prepare a "WASP-47 model system" with the currently observed orbital parameters of WASP-47 (see NASA Exoplent Archive), a Hot Jupiter (corresponding to WASP-47 b at the value of $a_{HJ} = 0.05$ AU), an inner companion which is an Ultra-Short Period (USP) Planet (corresponding to WASP-47 e at a = 0.0173 AU), and a nearby outer companion whose semimajor axis is fixed for this phase space analysis (corresponding to WASP-47 d). We fix the initial stellar obliquity to 10 degrees. Integrating using *Rebound* "ias15" integrator with *Reboundx* GR effects along a logarithmic J_2 evolution corresponding from 10^{-8} to 10^{-3}, we calculate the transit probability by averaging the state of the system over the last 10% of the integration. We plot the transit probability of outer planet and inner planet respectively across 500 randomly sampled simulations by varying semimajor axis of the inner and outer companion to the hot Jupiter.

Evolution Regimes

We discover a rich collection of regimes that result from the evolution of the systems with slightly modified initial orbital arrangements. Namely we discover that within our model WASP-47 modified systems, there are regimes in which:

a. The outer planet decouples dynamically from the hot Jupiter and leaves transiting plane (see upper right quadrant of Figure 3)
b. The inner USP planet experiences a drastic amplitude effect yet still usually- almost always, in our simulations- transits due to proximity to the star (see upper left quadrant of Figure 3), and the outer planet experiences some dynamical effect
c. The system remains generally stable with planets coupled but some form of dynamical action may occur near secular resonances; each planet is likely to transit (see lower left quadrant of Figure 3)
d. The outer planet experiences a major increase in amplitude which makes the outer planet likely to only sometimes transit (see lower right quadrant of Figure 3)
e. The system goes unstable in some fashion, whereby a planet is ejected or destroyed, and some uncoupling may also occur

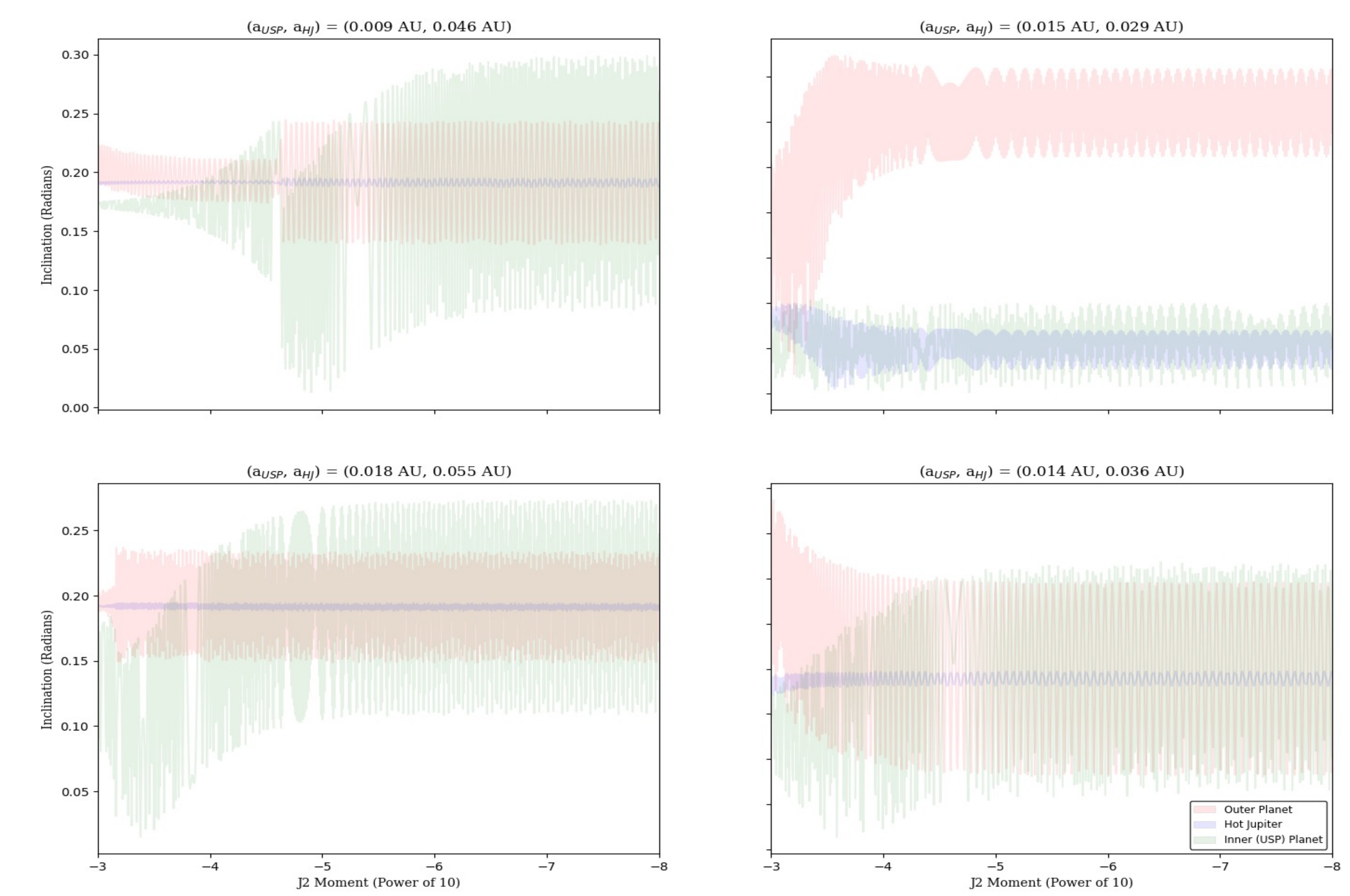


Figure 3 (left): Plots of distinct evolution regimes for "WASP-47 model system" across the evolution of the star. Inclination versus J_2 moment is shown for simulations that have different initial semimajor axes for the hot Jupiter and inner companion to the hot Jupiter (USP planet), given by some factor on the order of unity times the observed WASP-47 semimajor axis values (a_{USP}, a_{HJ}) = (0.0173 AU, 0.05 AU). The corresponding time evolution of inclination is along the direction of the x-axis, with time 0 corresponding to a J_2 of 10^{-3} and with the log-space of J_2 pictured corresponding to the linear time evolution from 0 to the end of the simulation which has $J_2 = 10^{-8}$.

Stellar Obliquity Role

We find that stellar obliquity is significant in detectability of a hot Jupiter's nearby outer companion; our results may indicate **a high likelihood of there being nearby outer companions to hot Jupiters which are undetected**. For systems with any stellar obliquity the transit probability for the outer companion drops off sooner and more quickly in simulations where the outer companion begins near the Hot Jupiter in the same transiting plane.as the initial semimajor axis (orbital period) of the outer planet is increased.

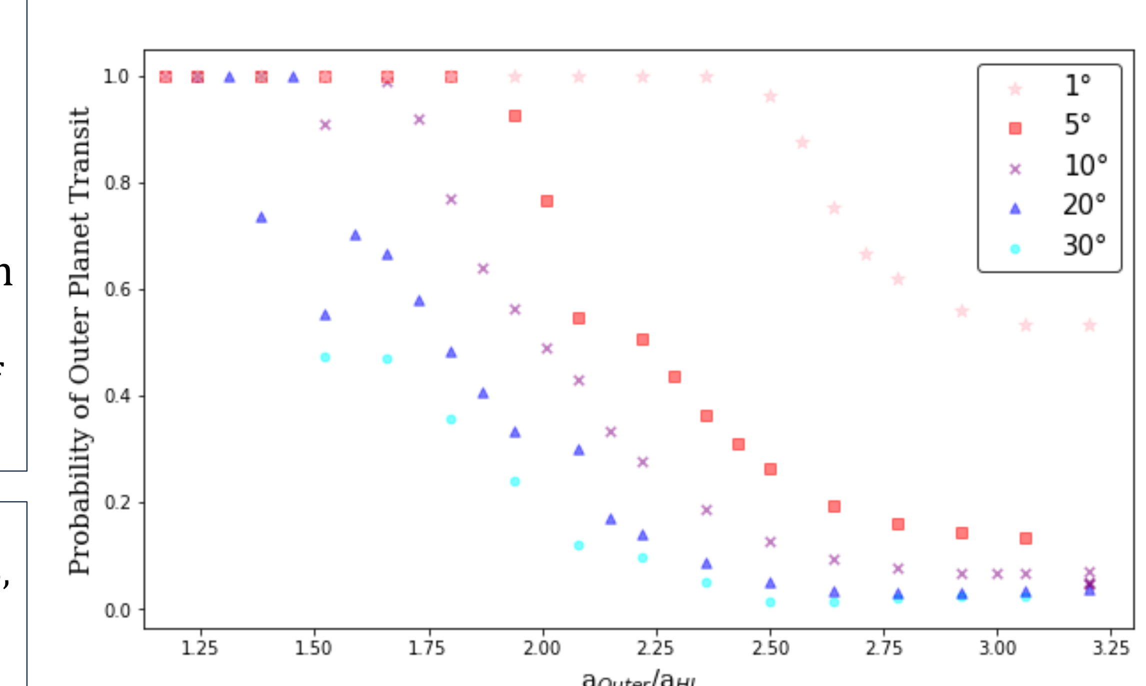


Figure 4 (right): "TOI-2000 model system," where points correspond to separate initial parameters, setting the star's obliquity at the start of integration to a fixed obliquity in {1, 5, 10, 20, 30} [degrees]. Simulations sampled across a change in initial semimajor axis for the outer companion to the hot Jupiter, with the x-axis corresponding to the semimajor axis ratio between the outer planet and hot Jupiter, and points were iteratively chosen to densify the plot in the y-direction to limit the plot's sensitivity to stochastic variation.

Conclusions

We find that there is a **rich phase space of evolutionary outcomes** resulting from orbital period differences, such that in some possible regimes **nearby outer companions to hot Jupiters are likely to leave the transiting plane and be undetectable**. Certain orbital period phase spaces correspond to decoupling of the nearby companion to the outer companion to the hot Jupiter so that the companion is not detectable. We also demonstrate that the stellar obliquity plays a role influencing the probability of the outer planet transiting, whereby larger stellar obliquities correspond to lower transiting probabilities.

References & Acknowledgements

Supported by Caltech GPS computing and funding, Prof. K. Batygin. Additional support by Caltech PMA.
J.C.B. has been supported by the Heising-Simons 51 Pegasi b postdoctoral fellowship.
This research has made use of NASA's Astrophysics Data System and NASA Exoplanet Archive.
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Data handling and presentation using NumPy, Pandas, Jupyter.