Investigating the Formation of Planets Interior to in situ Hot Jupiters

Devansh Mathur & Dr. Juliette Becker

Department of Astronomy, University of Wisconsin - Madison

Introduction

The presence of hot Jupiters poses a challenge to planet formation theories, particularly in the inner regions of protoplanetary disks. **In situ formation models** refer to those where Jupiter-mass planets accreted their envelopes while residing on short-period orbits [1,2].

These models are an attractive origin theory for, not only the formation of hot Jupiters, but also the formation of terrestrial inner companions observed in several hot Jupiter systems.

The ubiquity of these inner companions, as seen in **Figure 1** is not surprising: if hot Jupiters formed in situ and had detectable inner companions, those companions would likely remain in the same orbital plane as the hot Jupiter, regardless of the host star's obliquity or other dynamical influences.

In this study, we investigate the extent to which the in situ case is feasible through a suite of **N-body simulations**.

Figure 1: Observed hot Jupiter systems with inner companions.

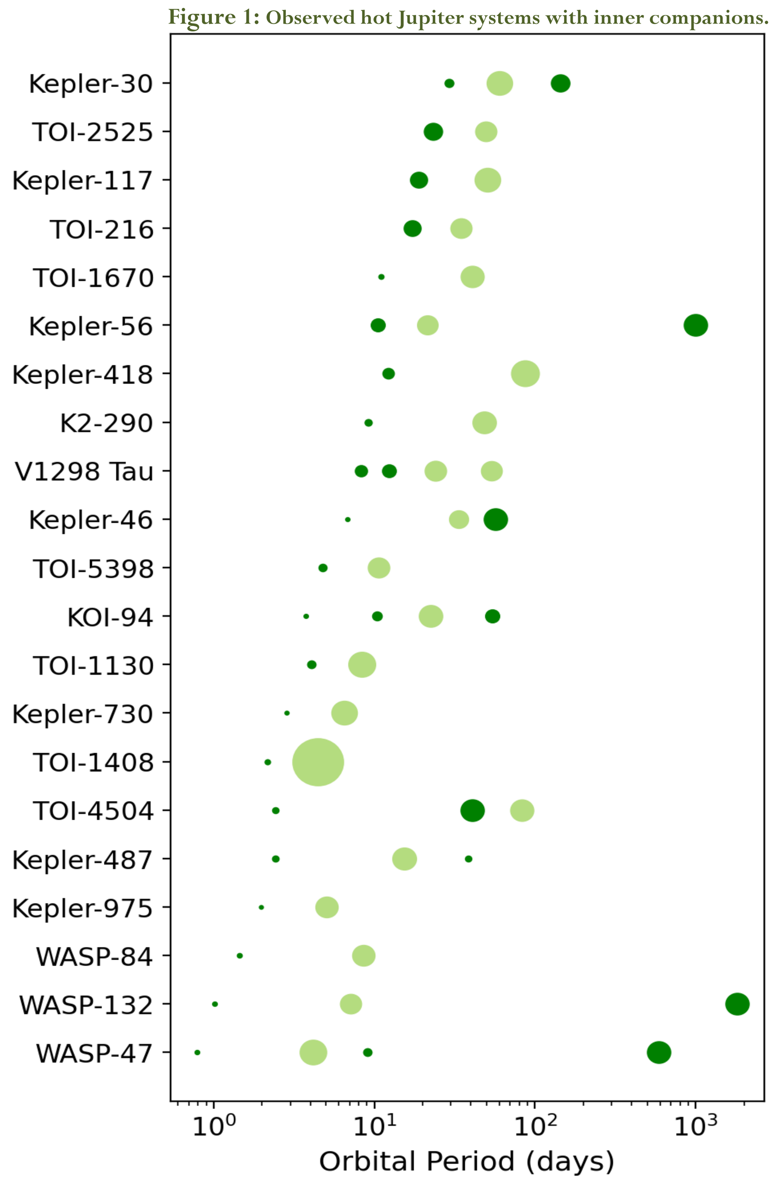
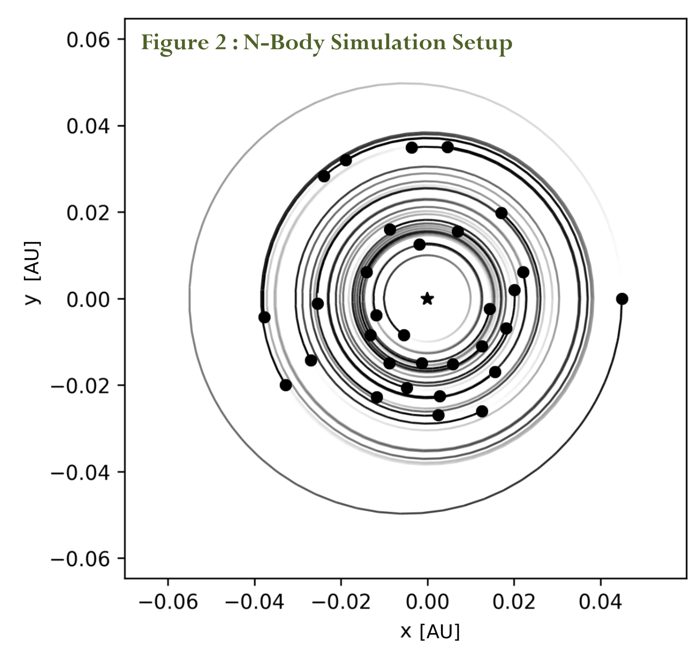


Figure 2 : N-Body Simulation Setup



Methods

All simulations are conducted using the **REBOUND**[3] package with the **TRACE**[4] integrator which dynamically adjusts the timestep during integration and is designed to accurately and efficiently resolve close encounters between bodies.

- **Effect of Surface Density on Planet Formation**

This suite of simulations was run to evaluate how varying the surface density of solid material affects the maximum planetary core mass that can be formed in close-in, gas-free environments.

For each simulation, we varied the total solid mass within a range consistent with a large range of plausible surface densities, sampled between roughly $5 \times 10^1 g/cm^2$ and $8 \times 10^5 g/cm^2$.

To assign individual embryo masses, we draw 30 values from a uniform distribution between these bounds, then divide the drawn values by 30 so that the total mass of all 30 embryos sums to reside in the chosen disk mass range.

- **Varying the Formation Location of the hot Jupiter**

Previously, we varied the surface density of planetary embryos while keeping the orbital distance of the hot Jupiter fixed. However, the orbital radius of the hot Jupiter will drive the scale of evolution for nearby planetary embryos.

Gravitational interactions between the hot Jupiter and the inner embryo disk can excite eccentricities and relative velocities in the disk, potentially leading to mergers, ejections, or destabilization of otherwise stable orbits. To examine this effect, we performed an additional suite of simulations in which we fix the total mass of planetary embryos and instead vary the orbital radius of the hot Jupiter.

Here, we vary the hot Jupiter's semi-major axis between 0.03 and 0.15 AU. This second simulation suite allows us to isolate how proximity to the giant planet affects planet growth and stability in an otherwise identical simulation setup to that used in the previous section.

Figure 3 : Simulated Planet Mass vs. surface density and inferred hot Jupiter core origin

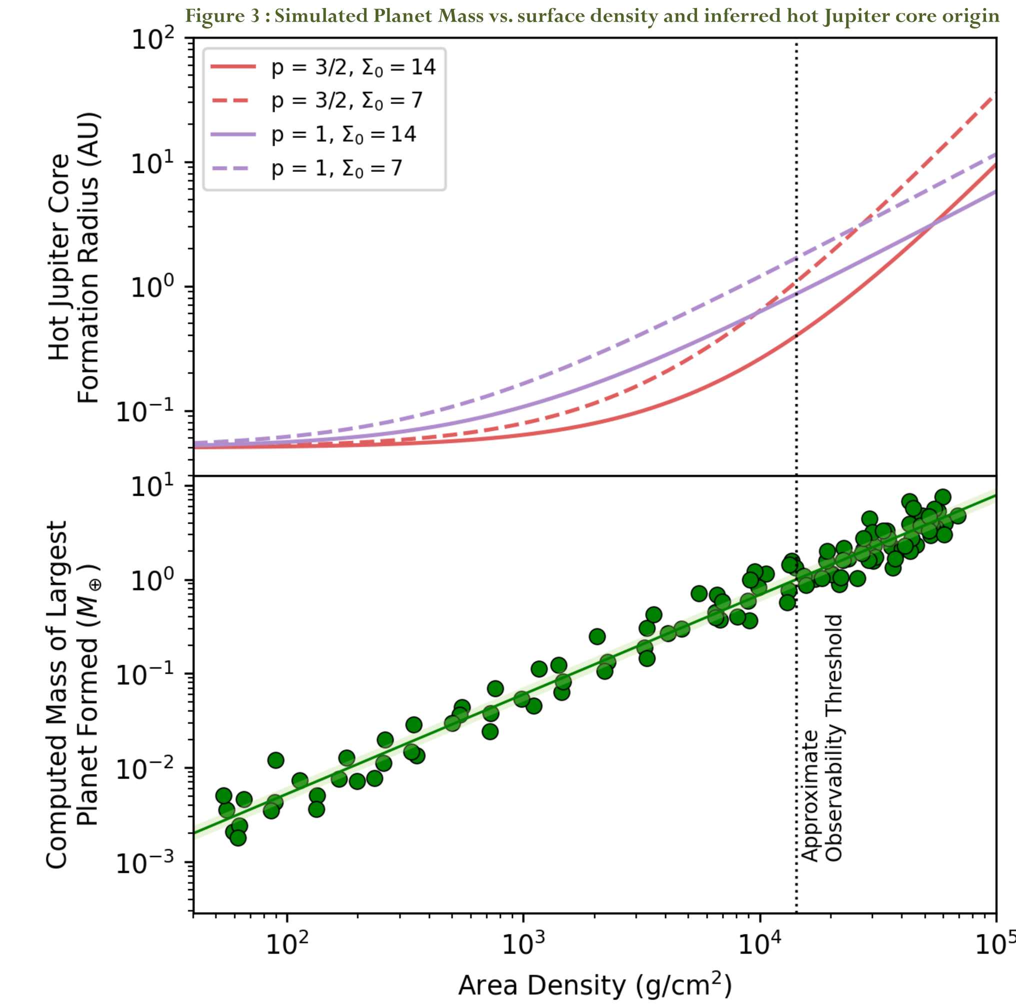
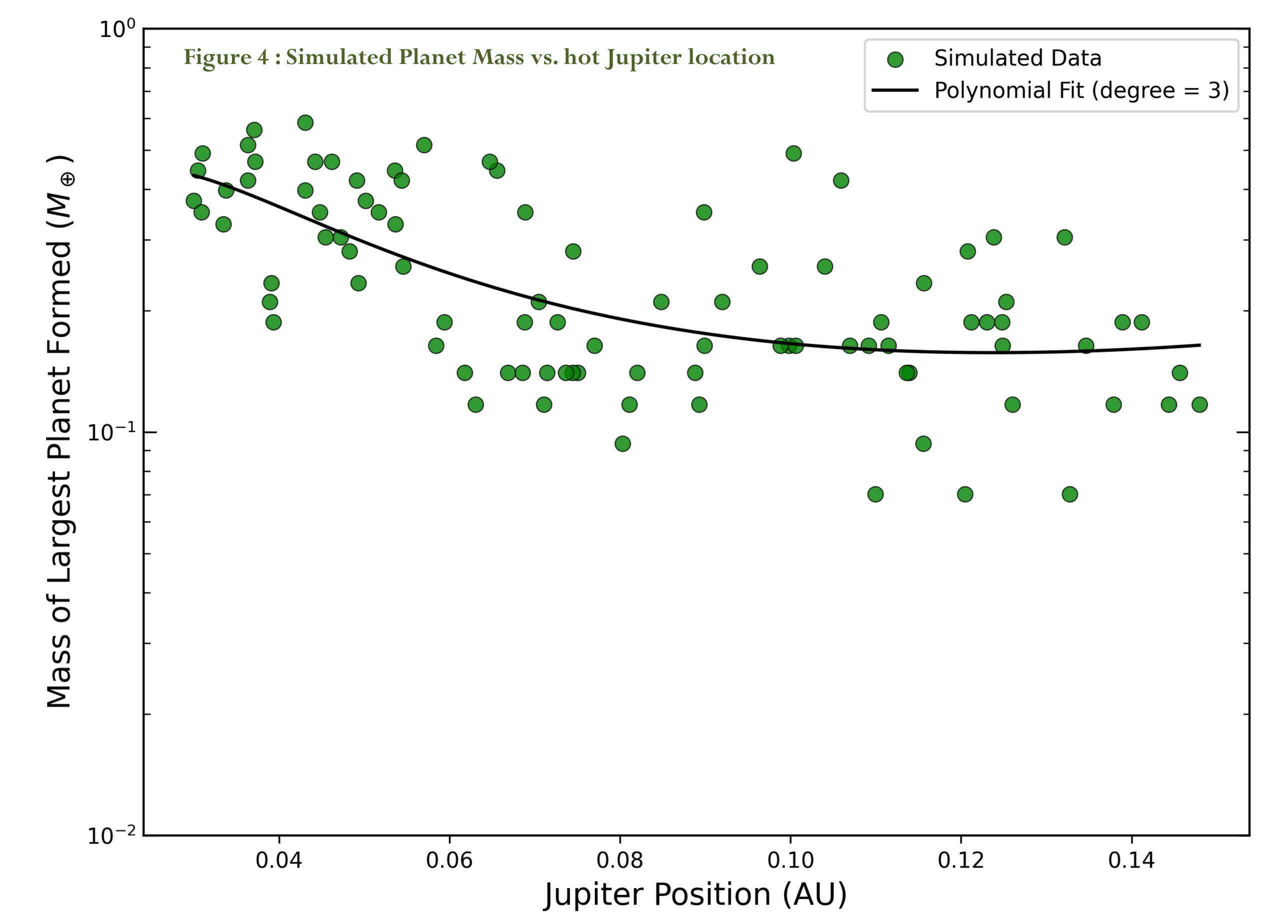


Figure 4 : Simulated Planet Mass vs. hot Jupiter location



Results

- **Effect of Planetary Embryo Surface Density**
  - Our simulations suggest that a hot Jupiter core likely formed beyond 0.4 – 0.16 AU, depending on disk model, to supply enough solids for inner planet formation. See **Figure 2**.
  - We find that higher surface densities consistently yield more massive planets, with frequent growth to ≥ 1 Earth mass. See **Figure 5**.
  - Our results show no evidence of growth suppression at high densities, indicating low relative velocities and efficient accretion even in crowded disks. See **Figure 2**.
  - Our simulations confirm that the initial inner disk mass budget is a key driver in determining the formation of detectable super-Earths.

- **Effect of the Hot Jupiter's Orbital Position**
  - We find that inner planet formation is most efficient when the hot Jupiter is at ~ 0.04–0.05 au. See **Figure 4**.
  - Our simulations show that the mass of the companion planet becomes insensitive to hot Jupiter position beyond ~0.10 au (warm Jupiter regime). See **Figure 4**.
  - We observe that the survival rates of embryos increase with larger hot Jupiter orbital distances. See **Figure 6**.
  - In the closest-in cases (<0.06 AU), our simulations show that only ~20% of embryos survive, indicating strong dynamical disruption.
  - At wider orbits (>0.08 AU), our results show that more embryos survive and grow, pointing to reduced loss through collisions or ejections. See **Figure 6**.

Figure 5 : Frequency Distribution of Massive Planets across surface densities

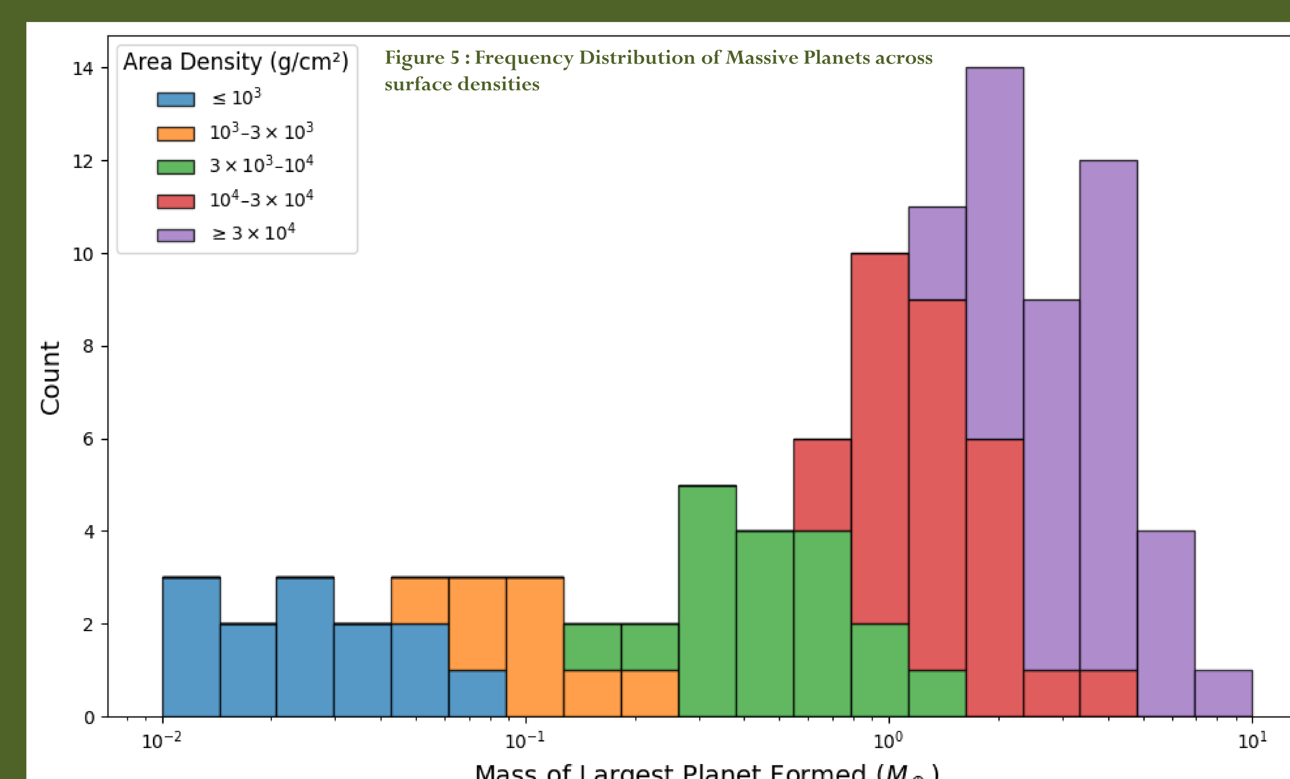
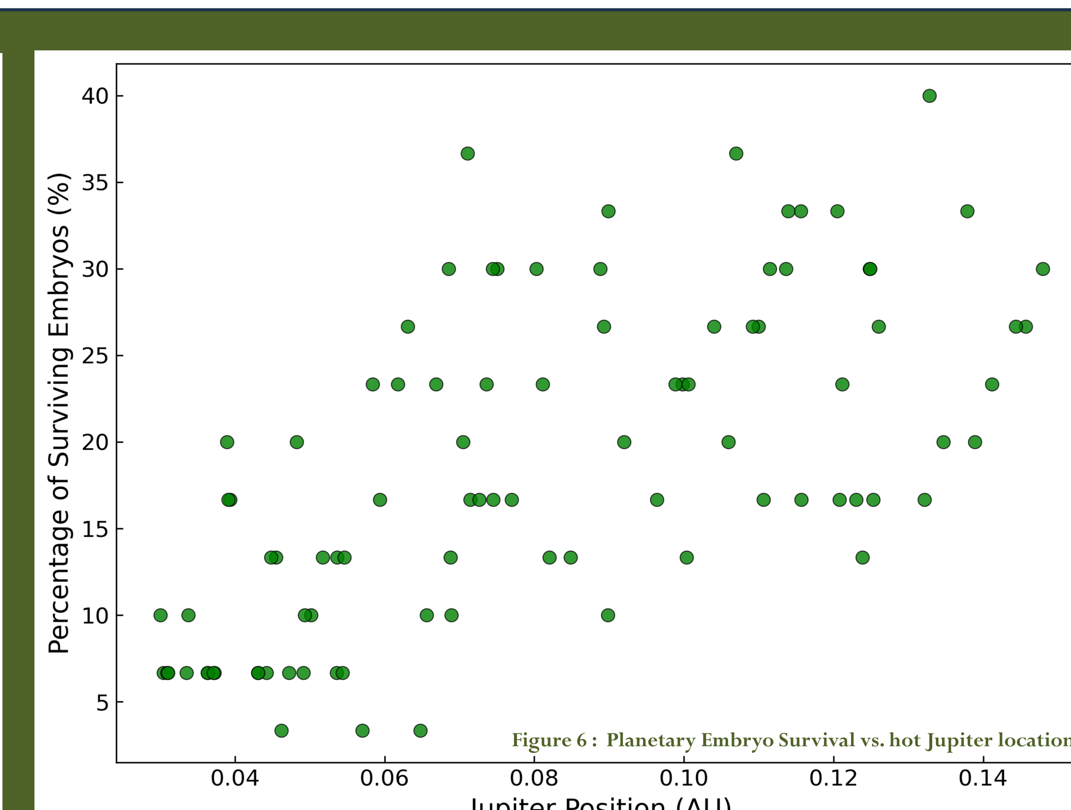


Figure 6 : Planetary Embryo Survival vs. hot Jupiter location



Citations

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2. Batygin, K., Bodenheimer, P. H., & Laughlin, G. P. 2016,586ApJ, 829, 114, doi: 10.3847/0004-637X/829/2/114587
3. Rein, H., & Liu, S. F. 2012, A&A, 537, A128,688doi: 10.1051/0004-6361/201118085689
4. Lu, T., Hernandez, D. M., & Rein, H. 2024, MNRAS, 533,6683708, doi: 10.1093/mnras/stae1982669