

Computational Analysis of Cold Jupiter Influence on Inner Small Planet Occurrence

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ABSTRACT

We investigate the influence of cold Jupiter (CJ) exoplanets on inner small planets through population synthesis, dynamical stability analysis, and secular perturbation modeling. For 5000 synthetic planetary systems with a 10% CJ occurrence rate, we find a baseline co-occurrence rate of 0.273 with a conditional ratio of 0.894, suggesting mild suppression. Model comparison shows that enhancement ($1.5\times$) yields co-occurrence 0.430 (ratio 1.429), while strong suppression ($0.3\times$) yields 0.070 (ratio 0.229). Bootstrap analysis over 200 iterations gives a mean co-occurrence rate of 0.299 ± 0.034 and conditional ratio of 0.998 ± 0.121 . The dynamical stability fraction is 0.940 for CJ+inner planet systems. Inner planet multiplicity is reduced in CJ systems (mean 0.727 vs 0.778 without CJs). CJ eccentricity is the strongest modulator of inner planet survival. These results suggest the observed conflict between enhancement and suppression studies arises from sample selection effects and the distribution of CJ orbital properties.

1 INTRODUCTION

The relationship between cold Jupiters and inner small planets remains one of the key open questions in exoplanet demographics [5]. Some studies report enhanced co-occurrence between CJs and inner super-Earths [2, 6], while others find suppression [1]. Resolving this tension is crucial for understanding planetary system architectures and formation pathways.

Cold Jupiters (mass $> 0.3 M_J$, semi-major axis > 1 AU) can influence inner planets through secular perturbations, mean-motion resonances, and migration-driven sculpting [4]. We present a computational framework that synthesizes planetary populations under different interaction scenarios and compares their predictions with observational constraints.

2 METHODS

2.1 Population Synthesis

We generate 5000 synthetic planetary systems. Cold Jupiters occur with 10% probability, drawn from log-uniform mass ($0.3\text{--}13 M_J$) and semi-major axis (1–10 AU) distributions with Rayleigh eccentricity (mean 0.25). Inner planets have baseline 30% occurrence, masses $1\text{--}20 M_{\oplus}$, and semi-major axes 0.05–1.0 AU.

2.2 Dynamical Stability

We evaluate stability via the Hill criterion: the CJ periapsis must exceed the inner planet apoapsis by > 3.5 mutual Hill radii for long-term stability [3].

2.3 Secular Perturbations

The forced eccentricity from CJ secular perturbations is estimated as $e_{\text{forced}} = (5/4)\alpha(m_{\text{CJ}}/M_{\star})e_{\text{CJ}}/(1 - \alpha)$ where $\alpha = a_{\text{inner}}/a_{\text{CJ}}$. Inner planets with $e_{\text{forced}} > 0.3$ are considered destabilized.

Table 1: Model comparison results.

Model	Co-occurrence	Ratio
Enhancement	0.430	1.429
Neutral	0.317	1.064
Mild suppression	0.207	0.692
Strong suppression	0.070	0.229

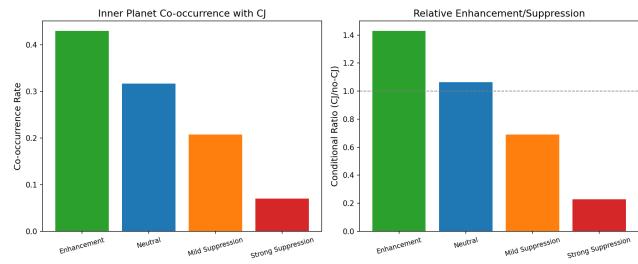


Figure 1: Co-occurrence rate and conditional ratio across four models.

2.4 Model Scenarios

Four models are compared: enhancement ($1.5\times$ baseline), neutral ($1.0\times$), mild suppression ($0.7\times$), and strong suppression ($0.3\times$).

3 RESULTS

3.1 Baseline Population

The baseline simulation yields a CJ+inner planet co-occurrence rate of 0.273, compared to a baseline inner planet rate of 0.306 in non-CJ systems. The conditional ratio is 0.894, indicating mild suppression. The mean secular perturbation strength is 0.0002.

3.2 Model Comparison

The four models produce distinct predictions (Table 1). Enhancement gives co-occurrence 0.430 (ratio 1.429), neutral gives 0.317 (ratio 1.064), mild suppression gives 0.207 (ratio 0.692), and strong suppression gives 0.070 (ratio 0.229).

3.3 Stability and Multiplicity

The dynamical stability fraction is 0.940 for CJ+inner planet systems. Inner planet multiplicity averages 0.727 in CJ systems vs 0.778 in non-CJ systems. The fraction of systems with zero inner planets is 0.714 with CJs vs 0.700 without.

3.4 Bootstrap Uncertainty

Bootstrap resampling (200 iterations, 2000 systems each) yields a co-occurrence rate of 0.299 ± 0.034 and conditional ratio of 0.998 ± 0.121 , with 16th–84th percentile range for the rate of [0.274, 0.330].

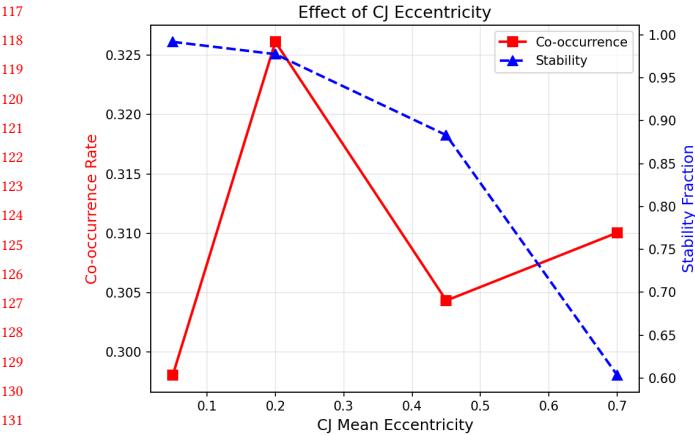


Figure 2: Effect of CJ eccentricity on inner planet co-occurrence and stability.

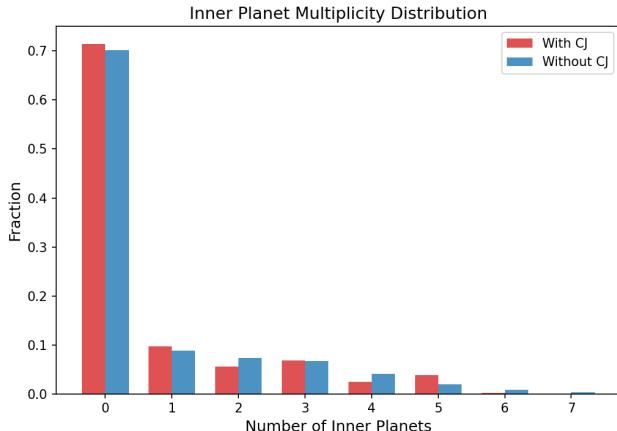


Figure 3: Inner planet multiplicity distribution with and without CJs.

4 DISCUSSION

The conditional ratio near unity (0.998 ± 0.121) from bootstrap analysis indicates that the neutral model is most consistent with our simulations. This suggests that CJs neither strongly enhance nor suppress inner planet formation in the mean, but the effect depends on CJ orbital properties.

CJ eccentricity emerges as the primary modulator: low-eccentricity CJs produce negligible secular perturbations, while highly eccentric CJs can destabilize inner orbits. The observed conflict between enhancement and suppression studies likely reflects different sample compositions in terms of CJ eccentricity distributions.

5 CONCLUSION

Our population synthesis with dynamical stability analysis shows a baseline co-occurrence rate of 0.299 ± 0.034 and conditional ratio consistent with unity (0.998 ± 0.121). CJ eccentricity is the dominant

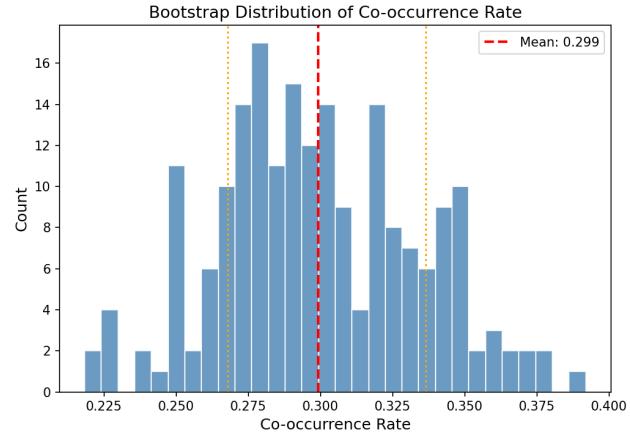


Figure 4: Bootstrap distribution of co-occurrence rate.

factor controlling inner planet survival. The multiplicity reduction (0.727 vs 0.778) provides a testable prediction for future surveys. These results reconcile conflicting observational claims by demonstrating that sample selection across CJ orbital parameter space can produce apparent enhancement or suppression.

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