Formation Mechanisms and Demographics of Cold Jupiters: A Computational Population Synthesis

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ABSTRACT

We present a computational investigation into cold Jupiter formation mechanisms using population synthesis with core accretion models, migration track reconstruction, and bias-corrected occurrence rate estimation. From 500 formation tracks, 455 (91.0%) produce giant planets with mean core mass $61.2\,M_\oplus$ (median $38.8\,M_\oplus$) and mean total mass $3.64\,M_J$. Migration analysis classifies 60.7% as in-situ, 14.3% as Type II, and 25.1% as scattering, with mean migration distance 1.57 AU. Bootstrap occurrence rate estimation yields a bias-corrected rate of $17.4\% \pm 0.5\%$ with survey completeness of 92.2%. Formation rates increase from 14% at [Fe/H] $= -0.5$ to 100% at [Fe/H] ≥ 0.3, and from 35% at $0.5\,M_\odot$ to 100% at $1.5\,M_\odot$, confirming strong metallicity and stellar-mass correlations.

1 INTRODUCTION

Cold Jupiters—giant planets ($> 0.3\,M_J$) orbiting beyond ~1 AU—represent a key population for understanding planet formation. Despite extensive observational efforts [1, 2], the precise formation mechanisms of cold Jupiters remain uncertain, with open questions regarding their core masses, migration histories, and overall occurrence rates across different stellar environments [6].

The core accretion paradigm [5] predicts that giant planets form via runaway gas accretion onto solid cores exceeding ~$10\,M_\oplus$ near or beyond the snow line. Population synthesis models [3, 4] have explored how disk properties and stellar parameters influence the resulting planet populations. Wu et al. [6] recently detected four cold Jupiters through joint radial-velocity and astrometry analysis, highlighting the need for expanded demographic studies.

1.1 Related Work

Pollack et al. [5] established the core accretion framework. Ida & Lin [3] developed deterministic population synthesis. Mordasini et al. [4] extended this to metallicity correlations. Cumming et al. [1] measured occurrence rates from RV surveys, while Fernandes et al. [2] identified a turnover at the snow line.

2 METHODS

Core Accretion Model. We model oligarchic growth of solid cores with solid surface density $\Sigma_s = 10 \times 10^{[\text{Fe/H}]}\, a^{-1.5}$ g/cm^2, enhanced by a factor of 4 beyond the snow line at 2.7 AU. Runaway gas accretion initiates when core mass exceeds $10\,M_\oplus$, with gas accretion capped by disk supply limits and an exponential disk dissipation timescale of 3 Myr.

Migration Reconstruction. Migration mechanisms are classified from final orbital elements: Type II for $a < 3$ AU, planet–planet scattering for $M > 3\,M_J$ and $e > 0.3$, and in-situ otherwise. Formation locations are back-calculated from observed semimajor axes.

Occurrence Rates. Detection probabilities are computed for RV surveys using K-amplitude sensitivity ($K > 3$ m/s threshold) and

Table 1: Cold Jupiter population synthesis results.

Property	Value
Formation tracks	500
Giants formed	455 (91.0%)
Mean core mass	$61.2\,M_\oplus$
Median core mass	$38.8\,M_\oplus$
Std. core mass	$66.3\,M_\oplus$
Mean total mass	$3.64\,M_J$
Core mass range	11.5–$596.9\,M_\oplus$
25th percentile	$23.1\,M_\oplus$
75th percentile	$69.2\,M_\oplus$

Table 2: Migration mechanism classification for 455 cold Jupiters.

Mechanism	Count	Fraction
In-situ	276	60.7%
Type II	65	14.3%
Scattering	114	25.1%
Mean migration	1.57 AU	
Median migration	1.40 AU	

orbital period completeness. Bias-corrected rates are obtained via inverse detection-probability weighting over 200 bootstrap iterations across a stellar population of 3000 stars with $M_\star \in [0.5, 1.5]\,M_\odot$ and [Fe/H] $\sim \mathcal{N}(0, 0.25)$.

3 RESULTS

3.1 Population Synthesis

Of 500 formation tracks spanning initial locations 2–15 AU, 455 (91.0%) produced giant planets. Table 1 summarizes the population properties.

3.2 Migration Mechanisms

Table 2 shows the migration classification. In-situ formation dominates at 60.7%, with scattering accounting for 25.1% and Type II migration for 14.3%. The mean migration distance is 1.57 AU (median 1.40 AU).

3.3 Occurrence Rates

Bootstrap estimation yields a bias-corrected occurrence rate of $17.4\% \pm 0.5\%$ with survey completeness of 92.2%. The raw detection rate is 16.1%.

3.4 Metallicity Dependence

Formation rates increase strongly with metallicity: from 14% at [Fe/H] = −0.5 to 72% at solar metallicity and 100% at [Fe/H] ≥ 0.3, consistent with the established planet–metallicity correlation.

3.5 Stellar Mass Dependence

Occurrence rates increase from 35% at $0.5\,M_\odot$ to 100% at $1.5\,M_\odot$, reflecting higher disk masses and more distant snow lines around more massive stars.

4 CONCLUSION

Our population synthesis confirms that cold Jupiters form efficiently via core accretion with median core masses of $38.8\,M_\oplus$. In-situ formation dominates (60.7%), with limited radial migration (mean 1.57 AU). The bias-corrected occurrence rate of 17.4% is consistent with RV survey estimates. Strong correlations with both stellar metallicity and mass support the core accretion framework, where higher metal content and disk mass produce more favorable conditions for giant planet formation.

5 LIMITATIONS AND ETHICAL CONSIDERATIONS

The core accretion model uses simplified physics without radiative transfer or magnetohydrodynamics. Migration reconstruction from final orbits is degenerate. The 3000-star sample limits statistical precision. No human subjects or sensitive data are involved.

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