Origin of Hot Jupiters

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Hot Jupiters

- Semi-major axis distribution of planets > 0.1 M_Jup

- ~1% of FGK stars have hot Jupiters

- How did Jupiters migrate from >1 AU to < 0.1 AU?
A New Migration Mechanism: Secular Chaos
(Wu & Lithwick 2011)

- Start with a few Jupiters beyond an AU, on widely-spaced, mildly eccentric & inclined orbits.

- Focus on secular (i.e. orbit-averaged) interactions. Okay if no close encounters or strong resonances.
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A New Migration Mechanism: Secular Chaos

- secular interactions can lead to chaos

- e.g., terrestrial planets’ orbits driven by secular chaos

(Laskar ’96)
An Example N-body Simulation

Initial conditions:

<table>
<thead>
<tr>
<th>a (AU)</th>
<th>ecc. (deg)</th>
<th>inc. (deg)</th>
<th>mass (Mjup)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.12</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>0.12</td>
<td>5</td>
<td>10</td>
</tr>
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<td>0.12</td>
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Secular Instability

Nothing happens for a long time...

![Graph showing the evolution of inclinations, eccentrics, and semi-major axes over time.](image)
Secular Instability

Inner planet

- Inner planet can reach high eccentricities & inclinations, given enough time
Secular Instability

When inner planet acquires high $e$,:
- pericenter approaches star
- tides raised by star can circularize planet
  $\Rightarrow$ hot Jupiter
- Inner planet has smallest "inertia" $\Rightarrow$ most likely to be excited
- Note also: remaining planets "cooled"
Another system (with tides & GR)

constant $a$ $\Rightarrow$ secular

$1\text{AU, } e=0.06, \text{ inc}=4\text{ deg, } 0.5\text{ MJ}$

$6\text{AU, } e=0.19, \text{ inc}=20\text{ deg, } 1.0\text{ MJ}$

$16\text{AU, } e=0.33, \text{ inc}=8\text{ deg, } 1.5\text{ MJ}$
Similar to Mercury’s orbital chaos

(Laskar & Gastineau ‘09)

Simulation

Lithwick & Wu (2011)

Theory
Has it really happened?

Michtchenko & Malhotra ‘04
Migaszewski & Gozdiewski ‘08,’09
## Comparison with Observations

<table>
<thead>
<tr>
<th>Observation</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-day pile-up</td>
<td>✓ gradual e-growth (timescale &gt; $10^6$ yrs) + tidal dissipation</td>
</tr>
<tr>
<td>Range of stellar obliquities (R-M)</td>
<td>✓ excite both e and i</td>
</tr>
<tr>
<td>Lack of close companions</td>
<td>✓ predict: no TTV for hot Jupiters</td>
</tr>
<tr>
<td>Masses lower than average</td>
<td>✓ more Jupiters beyond a few AU</td>
</tr>
<tr>
<td></td>
<td>✓ easier to excite low mass planets</td>
</tr>
</tbody>
</table>

Also predict that fraction of hot Jupiters increases with stellar age ⇒ no hot Jupiter around T Tauri
<table>
<thead>
<tr>
<th>Observation</th>
<th>Secular Chaos</th>
<th>Disk Migration</th>
<th>Kozai Migration</th>
<th>Planet Scattering</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-day pile-up</td>
<td>✓</td>
<td>X?</td>
<td>✓</td>
<td>X</td>
</tr>
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Also, cannot produce frequency of hot Jupiters (Wu et al.)
Also, initial conditions are artificial
Secular chaos predicts

\[ M \simeq M_J \left( \frac{\text{orbital period}}{1.9 \text{ days}} \right)^{-10/3} \]