Tidal and magnetic interactions between a hot Jupiter and its host star within a protoplanetary disk

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Outline

- Motivation
  - How the orbital evolution of a young hot Jupiter inside a magnetospheric cavity depends on the cavity size, planet mass, and orbital eccentricity.
- Description of the model
- Result
- Conclusion
Outline

- Introduction
- Description of the model
- Result
- Conclusion
Illustration of our simple model
Summarize the equations for the simulation

\[ \frac{de}{dt} = g_p + g* \]

\[ \frac{dR_p}{dt} = \left( \frac{\partial R_p}{\partial \alpha} \right)_{M_p=0} + \alpha \left( \frac{R_p}{M_p} \right) \dot{M}_p \]

\[ \frac{d\Omega_\ast}{dt} = -\frac{1}{I_\ast} \left\{ I_\ast \Omega_\ast - T_{disk} - \langle T_{planet} \rangle + M_p \left[ GM_* a (1 - e^2)^{1/2} \right] \right\} + \dot{\omega}_\ast \]

\[ \frac{da}{dt} = \frac{2ae \cdot e}{1 - e^2} + \frac{2\varepsilon \langle T_{planet} \rangle}{M_p an \sqrt{1 - e^2}} + \frac{2a J_\ast}{J_0} - \frac{2 \dot{M}_p a}{M_p} \]
Outline

- Introduction
- Description of the model
- Result
- Conclusion and discussion
Setting

- The orbital evolution of the planet is focused from $7 \times 10^5 \text{ yr}$ to $10^7 \text{ yr}$.

- Fixed parameter:
  - $M_\star = 1 \text{ Msun}$
  - $Q_\star' = 3 \times 10^5$
  - $Q_p' = 10^6$

- Varied parameter:
  - $B_0$: 1500G (larger cavity), 500G (smaller cavity)
  - $M_p$: 0.7M$_j$, 1M$_j$, 1.5M$_j$, 2 M$_j$
  - Eccentricity: $e_c$
  - $\varepsilon = 1$ (upper limit of the magnetic torque on the planet)
    - = 0 (absence of the magnetic torque)
Result

- Big cavity & $\epsilon = 1$
Result: $e_i = e_c - 0.01$

The position they can migrate the farthest in the end of the simulation.

Starting point: 2:1 resonance with the inner disk edge (0.45AU)

<table>
<thead>
<tr>
<th>$M_p$</th>
<th>0.7 Mj</th>
<th>1 Mj</th>
<th>1.5 Mj</th>
<th>2 Mj</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_c - 0.01$</td>
<td>0.21</td>
<td>0.27</td>
<td>0.35</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Result: $e_i = e_c$

- $M_p \leq 1 M_J$: Tidal inflation faster than inward migration
  - Overflow large Roche lobe at large $a$
  - Degeneracy is high
  - Runaway mass loss

- $M_p > 1 M_J$: Migrate inward without significant tidal inflation
  - Overflow small Roche lobe at small $a$; Stable L1 overflow
  - Migrate outward;
    - When the lighten planet gets larger
  - High degeneracy; Runaway
Big cavity & $\varepsilon = 0$

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<tr>
<td>$e_c$</td>
<td>0.21</td>
<td>0.27</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>→ 0.21</td>
<td>→ 0.28</td>
<td>→ 0.39</td>
<td>→ 0.38</td>
</tr>
<tr>
<td>$a$(AU)</td>
<td>0.032</td>
<td>0.032</td>
<td>0.025</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td>→ 0.03</td>
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<td></td>
<td>7</td>
<td>6</td>
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Result

- Small cavity $\Rightarrow a_{2:1} \approx 0.032\text{AU}$
Tidal and magnetic interaction

- The migration of less massive planets is more sensitive to the magnetic interaction, which is enhanced by their easily inflated radii.
- The migration of massive planets is more sensitive to the tidal interaction.
- Planets overflow with high degeneracy cause runaway mass loss.
Thanks for your attention!
Hot Jupiter: Jupiter-mass planets; Locate < 0.1 AU

Hot Jupiters have formed at larger orbital radii in the protoplanetary disk and then moved inward to their current locations via the disk-planet interactions (e.g. Lin et al. 1996)

Magnetic fields of CTTS are strong enough to truncate the inner regions of protoplanetary disk to the corotation radius and create an inner magnetospheric cavity.

The migration due to planet-disk interaction is expected to slow dramatically once a hot Jupiter passes the inner disk edge. Hot jupiters pile up at ≈0.04 AU (Gaudi et al. 2005)
Introduction

- Rice et al. (2008): planet’s entry into the magnetospheric cavity \( \Rightarrow \) orbital eccentricity \( e \uparrow \)
- Provide a mechanism to pump up \( e \Rightarrow \) affect the orbital evolution via the tidal interactions between the star and planet.

- The magnetic interaction between Jupiter and the Galilean satellites (Zarka 2007, and reference therein) \( \Rightarrow \) planet-star magnetic interaction

Description of the model

- Magnetic interaction
  - Star-disk magnetic linkage ➔ Disk locking
  - Star-planet magnetic linkage ➔ Orbital evolution

- Tidal interaction ➔ Circularization
  - Tides on the planet
    - Thermal inflation of the planet
  - Tides on the star
    - Orbital evolution
    - Evolution of the stellar spin

Illustration of our simple model

- The dipole fields of CTTS truncate the inner regions of protoplanetary disk and create an inner magnetospheric cavity.

- When the inner edge of the disk extends inward making $a > a_{2:1}$, then the planet is moved inward artificially to maintain $a = a_{2:1}$. 
Big Cavity $\Rightarrow a_{2:1} \sim 0.45\text{AU};$ $\varepsilon = 1$

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Big Cavity $\Rightarrow a_{2:1} \sim 0.45\text{AU}; \quad \varepsilon = 0$

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<tr>
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<td>0.036</td>
<td>0.03</td>
<td>0.016</td>
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