On the combined action of disc migration and planet-planet scattering in the formation of giant planetary systems

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Planetary System Architecture

- Observations: the orbits of extrasolar systems are more various than the circular and coplanar ones of the Solar system

- The search of Earth-like planets in the RV-detected planetary systems calls for a good understanding of giant planetary system architecture

- Limits of the observational methods: free parameters in the dynamical studies of the detected systems, especially the inclinations

- Idea: To resort to formation theories to have additional information about giant planetary systems
Late-stage formation of giant planetary systems

- **During** the disc phase: *Giant planet migration* (Type II)
  (e.g. Lin & Papaloizou 1986a, Kley 2000, Nelson et al. 2000)
  => eccentricity and inclination excitations
  (e.g. Thommes & Lissauer 2003, Libert & Tsiganis 2009, Teyssandier & Terquem 2014)

- **After** the disc phase: *Planet-planet scattering*
  (e.g. Weidenschilling & Marzari 1996, Ford & Rasio 2008, Juric & Tremaine 2008, Chatterjee et al. 2008)
  => eccentricity and inclination excitations
  + Initial conditions problem

- **Combined action** of both previous mechanisms:
  Planet-planet interactions **DURING** migration in the protoplanetary disc
  (e.g. Adams & Laughlin 2003, Matsumara et al. 2010, Libert & Tsiganis 2011)
  No inclination damping
Our work

**Generalization of** *Libert & Tsiganis 2011*

- 11 000 simulations of 3 giant planet systems in the late stage of the disc (SYMBA, $2 \times 10^5$ computational hours)
- planets with mass in $[1, 10] \ M_{\text{Jup}}$, initially outside the snowline, on quasi-circular and coplanar orbits
- different initial system configurations, planetary mass ratios, disc masses
- $\tau_{\text{II}}$=viscous accretion timescale $\times$ max $(1, \ M_p / \text{local disc mass})$
  *(Baruteau et al. 2013)* for the outer planet only
- exponential decrease of the disc mass, with a dispersal time of $\sim 1$ Myr
• eccentricity and inclination damping formulae
  provided by the 3D hydrodynamical simulations of Bitsch et al. 2013

**ECC**

\[
F_e(i_P) = -\frac{M_{\text{disc}}}{0.01 M_\star} \left(a (i_P + i_D)^{-2b} + c i_P^{-2d}\right)^{-1/2}
\]

\[
G_e(i_P, M_P, e_P) = 12.65 \frac{M_P M_{\text{disc}}}{M_\star^2} e_P \exp\left(-\left(\frac{(i_P/1^\circ)}{\tilde{M}_P}\right)^2\right)
\]

\[
a_e(M_P, e_P) = 80 e_P^{-2} \exp\left(-e_P^2 \tilde{M}_P / 0.26\right) \left(20 + 11 \tilde{M}_P - \tilde{M}_P^2\right)
\]

\[
b_e(M_P) = 0.3 \tilde{M}_P
\]

\[
c_e(M_P) = 450 + 2 \tilde{M}_P
\]

\[
d_e(M_P) = -1.4 + \sqrt{\tilde{M}_P}/6.
\]

**INCL**

\[
a_i(M_P, e_P) = 1.5 \times 10^4 (2 - 3 e_P) \tilde{M}_P^2
\]

\[
b_i(M_P, e_P) = 1 + \tilde{M}_P e_P^2 / 10
\]

\[
c_i(M_P, e_P) = 1.2 \times 10^6 \left[ (2 - 3 e_P) \left(5 + e_P^2 (\tilde{M}_P + 2)\right)^3\right]
\]

\[
d_i(e_P) = -3 + 2 e_P
\]

\[
g_i(M_P, e_P) = \sqrt{3 \tilde{M}_P / (e_P + 0.001)} \times 1^\circ
\]

\[
F_i(M_P, e_P, i_P) = -\frac{M_{\text{disc}}}{0.01 M_\star} \left[ a_i \left(\frac{i_P}{1^\circ}\right)^{-2b_i} \exp\left(-\frac{(i_P g_i)^2}{2}\right)
\right.

\[
+ c_i \left(\frac{i_P}{40^\circ}\right)^{-2d_i}\right]^{-1/2}.
\]

Valid for \(e<0.6\) and mass in \([1, 10]\) \(M_{\text{Jup}}\)

**Strong damping !**

de/dt=0.001/orbit, i.e. the planet will lose \(\sim 0.085\) in ecc in \(10^4\) yrs

di/dt=0.01°/orbit, i.e. the planet will lose \(\sim 8.5°\) of incl in \(10^4\) yrs
Goals

- Impact of the eccentricity and inclination damping on the final system configurations (a – e – i)
- Dynamical mechanisms producing inclination increase
- Mean-motion resonance captures during the gas phase
Dynamical mechanisms for inclination increase

Planet-planet scattering during the gas phase

- 1:3 MMR capture for the outer planets
- Subsequent increase of the eccentricities
- When the inner pair approaches the 3:7 commensurability, destabilization of the whole system
- Ejection of the inner less massive body
- Remaining planets in inclined orbits with large eccentricity variations and large orbital separation
Three-body resonance

- Capture in a 1:2:4 Laplace resonance
- Subsequent increase of the eccentricities
- When the eccentricities are high enough, inclination-type resonance
- Strong damping: planets back to the midplane
- Exponential decay of the gas disc: inclination-type resonance produces high inclinations maintained for a long time
Semi-major axis distribution

Best agreement for 16 $M_Jup$

Observations: exoplanets.org
Eccentricity distribution

Perfect agreement up to 0.35, lack of highly eccentric orbits
**Eccentricity distribution**

Removing single planet systems, good agreement up to 0.55

Perfect agreement up to 0.35, lack of highly eccentric orbits
Inclination distribution

3% of the systems have mutual inclination > 10° at the dispersal of the disc
Highly mutually inclined system in a Kozai-resonant state

- Capture in a three-body resonance + increase of the eccentricities and inclinations
- Destabilization of the system
- The remaining two-planet system is in a Kozai-resonance state with large eccentricities and inclinations variations of the inner planet + decoupling of the orbital eccentricities (Libert & Tsiganis 2009)
Long-term evolution

- Orbital adjustments due to planet-planet interactions can occur on a longer timescale AFTER the disc phase.

- Number of planets at 1.4d6 and 1d8:

<table>
<thead>
<tr>
<th></th>
<th>1 planet</th>
<th>2 planets</th>
<th>3 planets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4d6</td>
<td>7%</td>
<td>50%</td>
<td>40%</td>
</tr>
<tr>
<td>1d8</td>
<td>12%</td>
<td>53%</td>
<td>32%</td>
</tr>
</tbody>
</table>
No significant change on the semi-major axis and eccentricity distributions

Increase of the inclinations

5% of the systems have mutual inclination > 10° on long-time scale
Summary

- Good agreement between our simulations and the observed population of extrasolar systems
- Eccentricities well-diversified at the dispersal of the disc, despite the strong damping exerted by the disc
- Very efficient damping exerted by the disc on the inclinations: most of the planets end up in the midplane
- Inclination-type resonance and planet-planet scattering events during/after the gas phase induce inclination excitation: 5% of highly mutually inclined systems (>10°) in our population
- Future work: study of terrestrial planets in our population of giant planetary systems + their habitability
Thank you for your attention