On the feasibility of giant planet formation via disk gravitational fragmentation

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Giant planets: Mass vs. orbital distance

Approximately 40 planets in total

Core accretion domain

At $r > 10$ AU, the growth time of a solid core with $M > 10 M_{\text{Earth}}$ is greater than the mean gas disk lifetime, 2-3 Myr
Isolated disk models are misleading when studying disk gravitational instability and fragmentation.

Mass loading from infalling envelope is the key factor causing the disk to fragment (Vorobyov & Basu 2005, 2006).

Global models that self-consistently follow Cloud → Disk transition.

- **Pre-stellar phase**
  - Time: 0

- **Class 0 and I phases**
  - Time: 500 AU, 10,000 to 100,000 years

- **T Tauri phase**
  - Time: 100 AU, 100,000 to 3,000,000 years
Cons: Not full 3D. Two-dimensional thin-disk with approximate reconstruction of the vertical structure (not razor-thin!)

Pros: 1) Self-consistently follows cloud → disk formation
2) Long integration times (~ Myr)
3) High resolution (<1 AU at r<100 AU)
Long-term evolution of self-gravitating circumstellar disks

Initial conditions:

Collapsing cloud core with

\[ M_{\text{core}} = 1.07 \, M_\odot \]
\[ \beta = 0.7\% \]

\( \beta \) is the ratio of rotational to gravitational energy in the core.
Properties of fragments

Clump masses: 1 -- 100 $M_{\text{Jup}}$  
Clump radii: a few AU – a few tens of AU.

Adiabatic cores with rotation and pressure balancing self-gravity.

Number of fragments: up to 10, depending on the initial cloud mass and angular momentum
Disk fragmentation domain in the beta–$M_{\text{core}}$ phase space

Numbers in parentheses are disk radius [AU] and disk mass [$M_\odot$]

$M_{\text{core}} > 0.3 \, M_\odot$; $\beta > 0.3\%$, $M_{\text{disk}} > 0.07 \, M_\odot$

Vorobyov (2013)
Depending on the distribution of $\beta$-parameter (from 0.01% to 7%, Caselli et al. 2002), 40% - 70% of collapsing cores are supposed to form fragmenting disks (Vorobyov & Basu 2015).
Survival of fragments. Runaway inward migration.

Inward migration of fragments

Initial core mass = 1.0 M sun
Survival of fragments

\[ \Gamma_{\text{in}} = r \quad F_{\text{in}} > 0 \]
\[ \Gamma_{\text{out}} = r \quad F_{\text{out}} < 0 \]

\[ \frac{dL_{fr}}{dt} = \Gamma_{\text{in}} + \Gamma_{\text{out}} \]

Fragments may stay at quasi-stable orbits for as long as
\[ \Gamma_{\text{in}} > \text{abs} (\Gamma_{\text{out}}) \]

In the early phase this inequality almost always breaks due to
1) continuing disk growth via accretion from the infalling envelope.
2) sub-Keplerian velocity of the accreted material

Fragments need to form in the T Tauri phase to avoid fast migration (Vorobyov & Basu 2010; Kratter et al. 2010, Vorobyov 2013)
Formation and evolution of a fragmenting disk  \((M_{\text{core}} = 1.7 \, M_\odot; \, \beta = 0.56\%)\)

- Only one fragment finally survives.
- Two fragments survived through the embedded phase.
- The embedded phase ends at 0.65 Myr.
- Another episode of disk fragmentation in the T Tauri stage.
- The survived fragment opens a gap and settles on a quasi-stable orbit.
- Disk experiences vigorous fragmentation, but most fragment migrate onto the star.
Six models (out of >60) showing the formation of brown dwarfs and giant planets.

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Maximum eccentricity of the orbits is 0.07
## Comparison of models with observations

<table>
<thead>
<tr>
<th></th>
<th>modeling</th>
<th>observations</th>
<th>Conclusions and reasons for mismatch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object mass</td>
<td>3.5 – 43 ( M_{\text{Jup}} )</td>
<td>1.7 – 40 ( M_{\text{Jup}} )</td>
<td>• very wide separation planets (&gt;500 AU) fail to form because disks do not grow to radii &gt;&gt; 500 AU.</td>
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<td>Orbital distance</td>
<td>178 – 415 AU</td>
<td>10 – 7000 AU</td>
<td>• runaway inward migration of fragments hinders planet formation at radii &lt;150 AU</td>
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<td>Mass of the host star</td>
<td>0.75 – 1.2 ( M_{\odot} )</td>
<td>0.16 – 2.1 ( M_{\odot} )</td>
<td>• Low-mass stars (&lt;0.7 ( M_{\odot} )) have also low-mass disks – insufficient for gravitational fragmentation.</td>
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**Disk fragmentation cannot explain the whole spectrum of observed wide-orbit planets!**

Inward migration and tidal downsizing

High resolution

0.1—0.7 AU
in the inner 100 AU
Formation of giant planets revisited

Core accretion

Gravitational scattering?
(Dodson-Robinson et al. 2009)

Inward migration and downsizing of GI-formed clumps?
(Nayakshin 2010, Boley et al. 2010)

Gravitational capture?

Pebble accretion?
(Lambrechts & Johansen 2013)

In situ GI