Can disks form deuterium burning planets by core accretion?

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Garching, 6.11.2009 From circumstellar disks to planetary systems
Correlations with Disk Properties

**Metallicity (disk)**

- High [Fe/H]:
  - Higher number of giants (observed)
  - But not more massive (except for most massive)

**Disk mass (gas)**

- Disk mass changes the MF shape for giant planets.
- High disk mass: giant planets of higher mass, but less of lower mass.

**Disk lifetime**

- Disk lifetime changes both. Long living disks: giant planets are
  - More numerous and
  - Of higher mass
  - Correlation with \( M_D \)

Minimal dependence for Neptunes

Inversion at low masses: Distinguish detectable vs. actual existing planets!

- Many more correlations!

Mordasini et al. in prep
Rare, but there is a long tail of planets with masses clearly larger than 6-10 $M_{J}$. This are not (all) stellar companions nearly face-on. No discontinuity: smooth continuation. low numbers...
high mass tail of same formation mechanism?

Jupiter mass planets: formation by core accretion. What about these more massive objects?
Maximal Planet Mass - Gas Accretion

Low Mass Planets (M<30-100 M$_{\text{Earth}}$)

Limited by the planet itself, i.e. its ability to radiate away the energy released through the gravitational contraction of the gaseous envelope (Kelvin-Helmholtz timescale).

\[
\frac{dM_{p,g}}{dt} \sim \frac{M_p}{\tau_{KH}} \quad \tau_{KH} \approx 10^9 \left(\frac{M_p}{M_{\oplus}}\right)^{-3} \text{ years.}
\]

High Mass Planets (M>30-100 M$_{\text{Earth}}$)

The planet structure takes whatever the disk can feed. Limitation by global effects (disk dissipation, viscous transport to the planet) and/or local gas depletion (gap formation).

Obviously, cannot grow larger than total (late) disk (<0.1 M$_{\text{star}}$≈100 M$_{\text{J}}$)
**Limitation By Gap Formation**

Gap width increases with planet mass.
Gap width increases relative to size of Hill sphere.

“Classical” self-limitation to $6 - 10 \ M_J$ for planets.

\[
\frac{dM_{gas}}{dt} = M_{disk} \left( 1.668 \left( \frac{M_p}{M_J} \right)^{1/3} e^{-\frac{M_p}{1.5M_J}} + 0.04 \right)
\]

Disk accretion rate

Exponential decrease

---

**Table 1**

<table>
<thead>
<tr>
<th>Interval</th>
<th>Inner gap</th>
<th>Outer gap</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$ (a$_{\text{Jup}}$)</td>
<td>0.8</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>$a$ ($10^3$ a$_{\text{Jup}}$)</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td>$\dot{a}$ ($10^3$ a$_{\text{Jup}}$/yr)</td>
<td>0.0155</td>
<td>0.0044</td>
<td>0.0708</td>
</tr>
</tbody>
</table>

**References**

- Lin et al. 1996
- Lubow et al. 1999
- Veras & Armitage 2004
- Kley & Dirksen 2006
Sufficently massive planets (>3-5 \( M_j \)) can cause a sudden transition of the disk state from circular to eccentric.

- Eccentricity excitation at 1:3 outer Lindblad resonance is no more damped at 1:2 for sufficiently wide gaps, i.e. massive planets.

See also Papaloizou et al. 2001

Mass accretion onto the planet resumes strongly again. Maximum (on longer timescale) is:

\[
\frac{dM_{gas}}{dt} = \dot{M}_{disk}
\]

(Disk accretion rate)
Test Global Consequences

No limitation due to gap formation.
“Extreme Kley-Dirksen way”

With limitation
“Lubow et al. way”

As expected, strong influence for planets $\gtrapprox 6 \, M_J$

Planetary IMF

$M_{\text{star}}=1 \, \text{M}_{\odot}$

$f_1=0.001$

No irradiation
Planetary Initial Mass Function - High End

Without dM/dt limitation, \(\lesssim 0.4\%\) larger than 13 \(M_{J}\), with limitation, none.

Different slopes: better agreement without limitation.

Without dM/dt limitation, \(\lesssim 0.4\%\) larger than 13 \(M_{J}\), with limitation, none.

Rare, but there are now objects above the conventional planet - brown dwarf limit. Nature?
Pressure and temperature high enough in layers above the core to burn deuterium?

Baraffe, Chabrier & Barman 2008

“... We have considered a 25 $M_\text{J}$ planet with a 100 $M_\oplus$ core. Independently of the composition of the core material (water or rock), deuterium-fusion ignition does occur in the layers above the core. ... The same conclusion holds for a core mass of several 100 $M_\oplus$. ...”

Deuterium Burning Planets

New class of transition objects: Burn deuterium (like brown dwarfs), but have a formation and composition like planets.

OBSERVATIONAL HINTS?
Hints I: Radius Constraints

HD 147506b (Hat P-2b): 9.04 M\(\text{J}\)

CoRoT Exo 3b: 21.7 M\(\text{J}\)

Problem: Relative enrichment goes down with mass: very large planets are very efficient in ejecting planetesimal (rather than accreting them). Maybe different for collision scenario (Baraffe et al. 2008).

Gets more difficult to distinguish.
Absence of very massive planets at low [Fe/H] around solar type stars.

Not true for more massive stars.

Must build-up core very quickly.

Figure 8.

Fischer & Valenti 2005

Absence of very massive planets at low [Fe/H] around solar type stars.
Conclusions

- Can disks form deuterium burning planets by core accretion?
- Yes, IF eccentric instability mechanism occurs.
  - Interesting class of new objects between planets and brown dwarfs.
  - Make the 13 M$_J$ distinction even obscurer (cf. Chabrier et al. 2006)
  - Only if [Fe/H] > -0.2, M$_{\text{disk}}$ > 3 M$_{\text{MMSN}}$, T$_{\text{disk}}$ > 2 Myr.
  - Inside 10 AU.
  - Rather low eccentricities e<0.25.
  - (Slightly) smaller radius than brown dwarfs.
- Deuterium burning: depending not only on total mass
  - Internal composition matters (a little bit).
  - D-burning delays decrease of luminosity for first ≈ 10 Myr (compared to contraction only).
- Slope of high mass end of planetary IMF.
  - Imprint of disk properties? (cf. core mass function - stellar IMF)