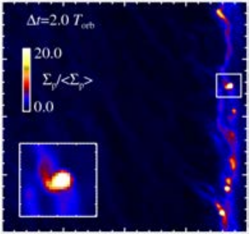
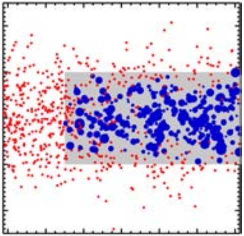
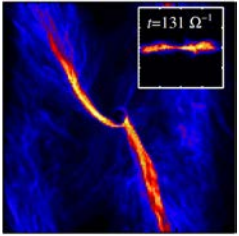
From pebbles to planets







Anders Johansen (Lund University)

with Michiel Lambrechts, Katrin Ros, Andrew Youdin, Yoram Lithwick

From Atoms to Pebbles – Herschel's View of Star and Planet Formation

Grenoble, March 2012

Overview of topics

Size and time ⟶

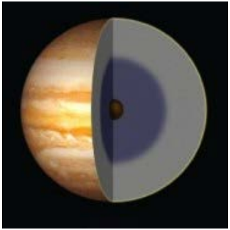
Dust	Pebbles	Planetesimals	Planets
μm	cm	10–1,000 km	10,000 km

1. From dust to pebbles by ice condensation
   Ros & Johansen (in preparation); poster by Katrin Ros

2. From pebbles to planetesimals by streaming instabilities
   Johansen, Youdin, & Lithwick (2012)

3. From planetesimals to gas-giant cores by pebble accretion
   Lambrechts & Johansen (submitted); poster by Michiel Lambrechts

Classical core accretion scenario



1. Dust grains and ice particles collide to form km-scale planetesimals
2. Large protoplanet grows by run-away accretion of planetesimals
3. Protoplanet attracts hydrostatic gas envelope
4. Run-away gas accretion as $M_{\rm env} \approx M_{\rm core}$
5. Form gas giant with $M_{\rm core} \approx 10 M_\oplus$ and $M_{\rm atm} \sim M_{\rm Jup}$

Planetesimal accretion

- Planetesimals passing within the Hill sphere get significantly scattered by the protoplanet
- The size of the protoplanet relative to the Hill sphere is

$$\alpha \equiv \frac{R_\mathrm{p}}{R_\mathrm{H}} \approx 0.001 \left(\frac{r}{5\,\mathrm{AU}}\right)^{-1}$$

- Rate of planetesimal accretion

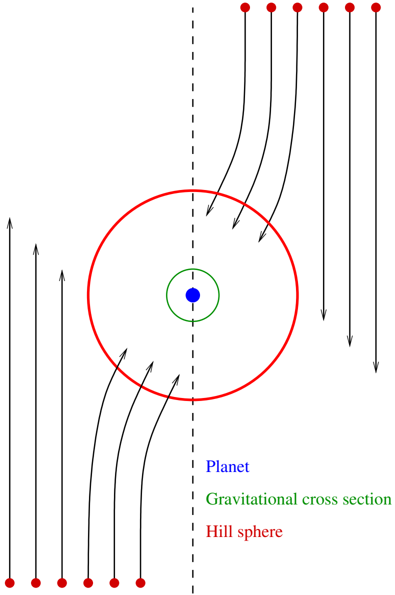
$$\dot{M} = \pi R_\mathrm{p}^2 \mathcal{F}_\mathrm{H}$$

- Without gravitational focusing

$$\dot{M} = \alpha^2 R_\mathrm{H}^2 \mathcal{F}_\mathrm{H}$$

- With gravitational focusing

$$\dot{M} = \alpha R_\mathrm{H}^2 \mathcal{F}_\mathrm{H}$$



Core formation time-scales

- The size of the protoplanet relative to the Hill sphere:

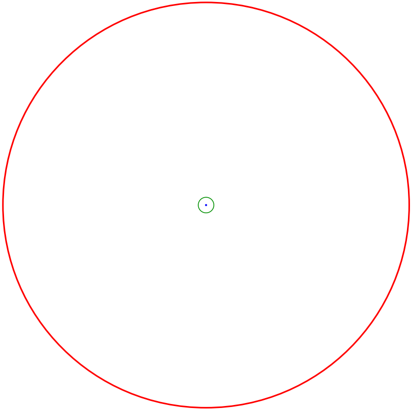
$$\frac{R_{\rm p}}{R_{\rm H}} \equiv \alpha \approx 0.001 \left(\frac{r}{5\,{\rm AU}} \right)^{-1}$$

- Maximal growth rate

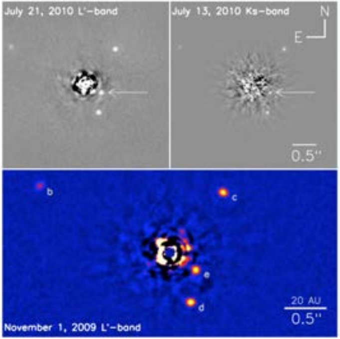
$$\dot{M} = \alpha R_{\rm H}^2 \mathcal{F}_{\rm H}$$

$\Rightarrow$ Only 0.1% (0.01%) of planetesimals entering the Hill sphere are accreted at 5 AU (50 AU)

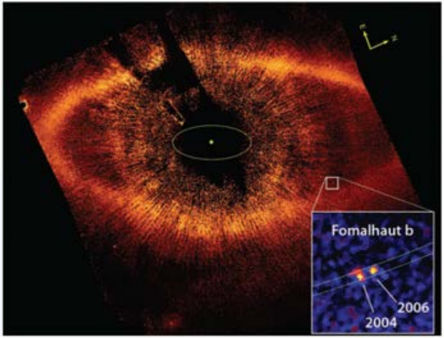
$\Rightarrow$ Time to grow to 10 $M_\oplus$ is
$\sim$10 Myr at 5 AU
$\sim$50 Myr at 10 AU
$\sim$5,000 Myr at 50 AU



Directly imaged exoplanets



(Marois et al. 2008; 2010)

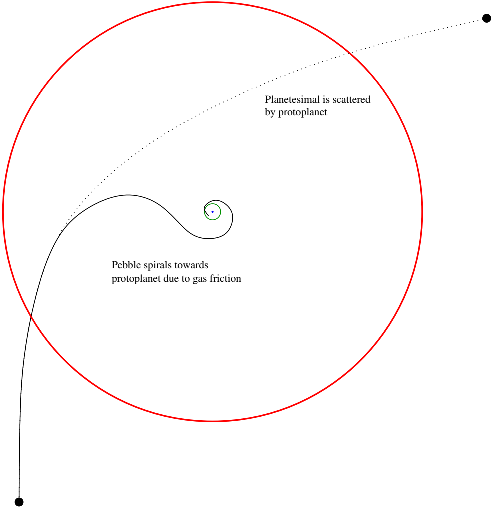


(Kalas et al. 2008)

- HR 8799 (4 planets at 14.5, 24, 38, 68 AU)
- Fomalhaut (1 planet at 113 AU)

⇒ No way to form the cores of these planets within the life-time of the protoplanetary gas disc *by standard core accretion*

Pebble accretion



- Most planetesimals are simply scattered by the protoplanet
- Pebbles spiral in towards the protoplanet due to gas friction

⇒ Pebbles are accreted from the entire Hill sphere

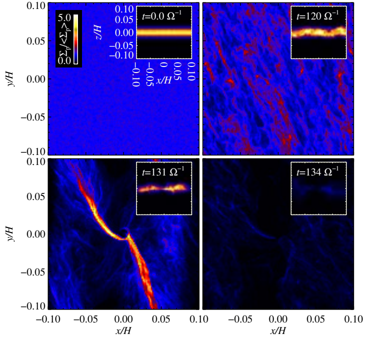
- Growth rate by planetesimal accretion is

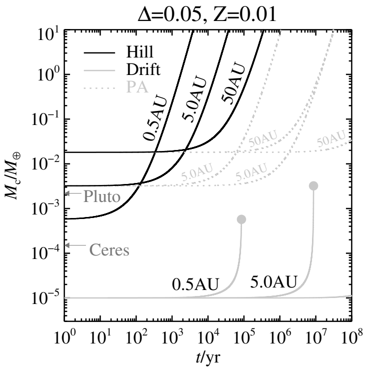
$$\dot{M} = \alpha R_{\mathrm{H}}^2 \mathcal{F}_{\mathrm{H}}$$

- Growth rate by pebble accretion is

$$\dot{M} = R_{\mathrm{H}}^2 \mathcal{F}_{\mathrm{H}}$$

Time-scale of pebble accretion





⇒ Pebble accretion speeds up core formation by a factor 1,000 at 5 AU and a factor 10,000 at 50 AU

(Lambrechts & Johansen, submitted to A&A; see also Ormel & Klahr 2010)

⇒ Cores form well within the life-time of the protoplanetary gas disc, even at large orbital distances

- But requires large planetesimals to begin with. . .

Formation of large planetesimals

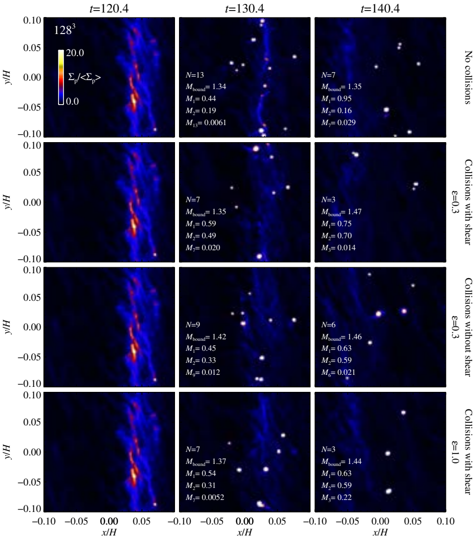
- Streaming instabilities lead to concentration of cm-sized pebbles
  (Johansen & Youdin 2007; Bai & Stone 2010)
- Planetesimals with $d \sim 1000$ km form by gravitational collapse

⇒ Asteroids born big?
(Morbidelli et al. 2009)

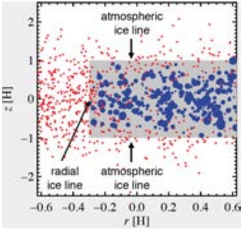
- Scaling to Kuiper belt gives twice as large planetesimals
  (Johansen, Youdin, & Lithwick 2012)

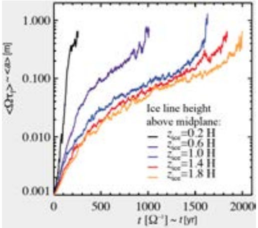
⇒ Explains why Kuiper belt objects are larger than asteroids

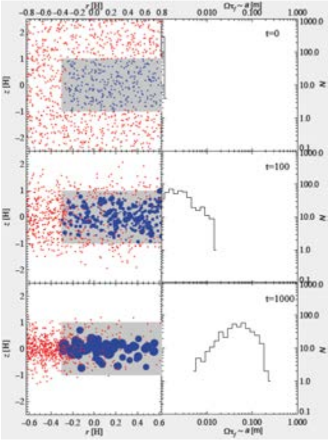
⇒ Largest planetesimals can grow to cores by pebble accretion



Formation of icy pebbles



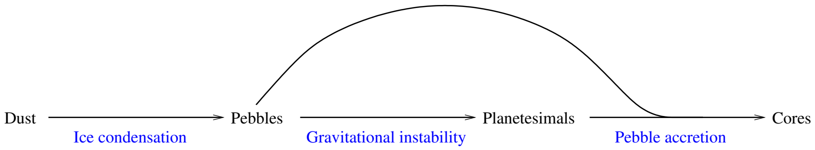




- Pebbles are observed in abundance in nearby protoplanetary discs
  (e.g. Testi et al. 2003; Wilner et al. 2005)
- How do pebbles form so efficiently?
- *Near ice lines pebbles can form like hail stones*

⇒ Efficient formation of cm-dm sized icy pebbles near ice lines
(Ros & Johansen, in preparation; poster by Katrin Ros)

Summary of talk



1. *Ice condensation leads to efficient formation of pebbles near ice lines*
   (Ros & Johansen, in preparation; poster by Katrin Ros)
2. *Streaming instabilities form large planetesimals (∼Ceres or ∼Pluto)*
   (Johansen, Youdin, & Lithwick 2012)
3. *Large planetesimals grow rapidly by pebble accretion, explaining the giants of the solar system as well as gas giants in wide orbits*
   (Lambrechts & Johansen, submitted; poster by Michiel Lambrechts)

⇒ Icy pebbles may play important role in planet formation

⇒ Planet formation can be probed and constrained through observations of water vapour and pebbles