The formation of gas giants and ice giants by pebble accretion
Planets and pebbles in protoplanetary discs

1. Planets form in protoplanetary discs (few Myr, in wide circular orbits, and in multiples)
2. Simultaneously, there is a large solid component in pebbles (mm-dm sized particles)

**HD100546, 2Msol, ~5Myr.**
- 400 AU wide ppd
- Potential imaged gas giant planet at 53 AU
(Quanz et al 2014)

**TW Hya ppd (~5Myr) [left]**
- 80 AU planet of 6-28 ME
- ~180--300 Me in pebbles
(Wilner+2005, bergin+2013)

**HL tau ppd (~1Myr) [right]**
- Formation of planets in a ~1Myr old disc
- Large pebble component
(Greaves et al 2008)

Debes et al 2013
ALMA collaboration+, 2015
Pebble accretion dynamics

Bondi pebble accretion
Lambrechts & Johansen, 2012
Pebble accretion dynamics 2

Hill regime starts above a transition mass:

\[ M_t \approx 3 \times 10^{-3} \left( \frac{r}{5\text{AU}} \right)^{3/4} M_{\oplus} \]

- accretion occurs from the full Hill radius

\[ t_{\text{cross,Hill}} \sim \Omega_K^{-1} \sim t_{\text{drag}} \]

- relative velocities are set by the Keplerian shear (independent of \( \frac{M_c}{M_t} \))
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- relative velocities are set by the Keplerian shear (independent of \( M_c \))
Difference with planetesimals

\[ \dot{M}_{\text{peb}} \sim r_H v_H \Sigma_{\text{peb}} \quad \quad \quad \quad \quad \quad \dot{M}_{\text{plan}} \sim r_{\text{acc}}^2 v_H \rho_{\text{plan}} \]

- \( \rho_{\text{plan}} \sim \Sigma_{\text{plan}} / h_{\text{plan}} \)
- \( h_{\text{plan}} \sim v_H / \Omega_K \sim r_H \)
- \( \alpha = r_{\text{acc}} / r_H \)

\[ \sim 10^{-2} (r/5\text{AU})^{-1/2} \]

See also:
Ormel & Klahr 2010
Rafikov 2004 planetesimals/fragments
and Levison et al 2010
An analytic “toy model”

\[ \Sigma_p(r, t) + \tau_f(r, t) \rightarrow M_{c,p}(r, t) \approx 2(\tau_f/0.1)^{2/3} r_H v_H \Sigma_p \]

Birnstiel et al, 2012

Lambrechts and Johansen, 2014
Pebble drift planets

- start with compact configuration of 4 embryos

- few Myr in disc with pebble surface density reduced by a factor ~5 with respect to MMSN

- inside out planet formation

- pebble flux filtering

\[
    f = \frac{\dot{M}_c}{\dot{M}_F} = \frac{5}{\pi} \left( \frac{\tau_f}{0.1} \right)^{-1/3} \eta^{-1} \left( \frac{r_H}{r} \right)^2 \\
    \approx 0.034 \left( \frac{\tau_f}{0.1} \right)^{-1/3} \left( \frac{M_c}{M_E} \right)^{2/3} \left( \frac{r}{10 \text{ AU}} \right)^{-1/2}
\]

17% for one core and about 50% for a ‘Solar System’

- mass budget:
  total mass: ~120-160 Me
  terrestrial mass: 50 Me/2 (inside the ice line)
Characteristics of the model

- overcome type I migration
  ice giants form ~ in situ
  -> cross over mass
  \[ M_c^* \approx 26 \left( \frac{\tau_f}{0.05} \right)^{8/9} \left( \frac{Z_0}{0.01} \right)^{5/8} \left( \frac{r_0}{10 \text{AU}} \right)^{9/16} M_E. \]

- steep initial dust-to-gas ratio dependency
  \[ M_c(t) \propto Z^{25/6}. \]

For more talk by Bert!
The core accretion scenario

Core accretion with pebbles:

- rapid formation of the core without enhancements of the solid surface density
- faster contraction of the gaseous envelope, because of pebble isolation mass
- particular attention at forming ice giants
The critical core mass

Lambrechts et al 2014

- Protoplanetary disc lifetimes constrain accretion rates to be high to complete cores

- Critical core mass increase with accretion rate (Rafikov 2006)

- The high accretion rates necessary to form the cores lead to core masses much too large compared to the gas giants in the Solar System

- Therefore halting the accretion is a necessity in the core accretion scenario (or a lot of ice pollution)
The pebble isolation mass

- gravity of the core perturbs gas disc
- creates a pressure bump (shallow gap) that traps particles outside the accretion radius, thereby halting solid accretion
- pebble isolation mass $\sim$ critical core mass

$M_{\text{iso}} \approx 20 \left( \frac{r}{5 \text{AU}} \right)^{3/4} M_{\text{Earth}} \propto \left( \frac{H}{r} \right)^3$
Ice giant / gas giant divide

- radial and compositional dichotomy between gas and ice giants

- gas giants in the inner disc (<10 AU) reach isolation and therefore undergo runaway gas accretion

- ice giants have not undergone isolation (or only briefly). The blue lines show the least polluted envelope that can be bound to the core.

Lambrechts et al 2014
Exoplanets with envelopes

Data from open exoplanets catalogue
Expanding the scenario

• full disc models see following talk by Bertram Bitsch

• terrestrial embryo/planet formation
  (Guillot+2014, Johansen+2015, Morbidelli+2015, Levison/Kretke group+2015, Lambrechts in prep)

• (hybrid) N-body codes

• doing the gas envelope contraction carefully
  Piso & Youdin 2014, Mordasini+a,b 2014, Ormel, 2014
Questions?

- formation in a few Myr
- halting solid accretion (~20 Me) form gas giants and ice giants
- dust-to-planet efficiency (~50%)
- metallicity correlation (steep)
- overcome type I migration

Lambrechts & Johansen, 2014
Lambrechts, Johansen, Morbidelli, 2014
Lambrechts & Johansen, 2012
Morbidelli, Lambrechts +, 2015 submitted
Bitsch, Lambrechts & Johansen, 2015 submitted