First Steps of Planet Formation

Katherine Kretke (NPP SSERVI Fellow)
Classical Model - Planetesimals

Runaway

Oligarchic

Mass Limited by isolation mass (as long as the planetesimals are cool).
Classical Model - Planetesimals

Runaway

Oligarchic

Mass Limited by
Growth of Dust

eg. Seizinger, Speith, Kley (2012)

e.g. Blum et al 2014
Growth of Dust

eg. Seizinger, Speith, Kley (2012)

e.g. Blum et al 2014
Challenges to Particle Growth

- Fragmentation
- Compaction & Bouncing
- Radial Drift

e.g. Birnstiel et al. (2012)
Observational Evidence of “pebbles”

Wilner et al. 2017

Pinte et al. 2016
In the inner regions, article growth is likely limited by fragmentation.
Pebbles may clump and form planetesimals!

Streaming Instability: Youdin & Goodman (2005)
Also turbulent clumping e.g. Cuzzi (2010)
e.g. Johansen et al. (2007)
The Streaming Instability Needs a lot of Pebbles

Yang et al 2016, Carrera et al 2015

\[ \text{Stoke's Number} \]

\[ 0.01 \quad 0.1 \]

\[ 1 \text{ mm} \quad 1 \text{ cm} \quad 1 \text{ dm} \quad 1 \text{ m} \]

\[ 0.1 \text{ AU} \quad 1 \text{ AU} \quad 10 \text{ AU} \quad 100 \text{ AU} \]

\[ \text{St} = 0.1 \]
Signs of Planetesimal Formation by Gravitational Instability

Nesvorny, Youdin, Richardson (2010)
Signs of Pebbles in Comet C-G from Rosetta

- MIRO: areal diurnal temperature variations
- MUPUS-TM: local diurnal temperature variations
- Dust-size distributions derived from Rosetta observations by COSIMA, GIADA, OSIRIS and from the ground.
- Tensile-strength values derived from various Rosetta observations correspond to dust-aggregate sizes according to Skorov & Blum 2012 model.
- CIVA: direct imaging of dust “pebbles” from Philae.

Blum et al. (subm. to MNRAS) slide courtesy of Jürgen Blum
Signs of Planetesimal Formation by Gravitational Instability

Starting from 10 km planetesimals

Starting from 100-1000 km planetesimals

Morbidelli et al 2009
Pebbles + Planetesimals = Pebble Accretion


Lambrechts & Johansen (2012)
Solves a problem in Giant Planet Core Formation!

Large planetesimals = too slow of formation  
Small planetesimals = gaps not growth

e.g. Thommes & Duncan 2006  
Levison et al 2010
Solves a problem in Giant Planet Core Formation!

Large planetesimals = too slow of formation
Small planetesimals = gaps not growth

e.g. Thommes & Duncan 2006

Levison et al 2010
Pebbles can form Giant Planet Cores

Levison, Kretke & Duncan (2015)
Less clear in the terrestrial planet region

**Pebble Accretion**

- Initial surface density of planetesimals
- Mass limited by: Pebble Flux

**Planetesimal Accretion**

- Initial surface density of planetesimals
- Pebble Flux

Levison, Kretke et al 2015

Walsh & Levison in prep

Katherine Kretke – Origins of Volatilizes in Habitable Planets – Ann Arbor, MI
Either way, the final stage of terrestrial planet formation similar to

Levison, Kretke et al 2015
Depends on size of planetesimals, pebbles, and disk structure

Different Assumptions of Disk Structure

(a) irradiation regime

(b) viscous regime

(c) irradiation+viscous

(d) irr+vis w/ general $\tau_s$

(e) full with sublimation

Ida et al. 2016

Downside – Results depend sensitively on difficult to measure parameters
Upside – Natural Source of Exoplanet Variability!

Shorter Formation Times

Different Assumption of Pebble Properties
A source of short period planets?

Chatterjee & Tan (2014)
Or... You can just move the planets

Type I – low mass planets

Type II – high mass planets

e.g. Armitage & Rice (2005)

e.g. Minton & Levison (2012)
Evidence for Migration

Kepler 223

Mills et al 2016

Our Solar System
Direction of Type I migration

Paardekooper et al 2010 e.g. Kretke & Lin 2012

Benitez-Llambay et al 2015
Type I Migration still a problem

Even with pebble accretion, icy planets are predicted to migrate substantially

Fulton et al 2017

Short period super Earths appear rocky

Bitsch et al 2015
Type II migration in our Solar System?

Masset & Snellgrove (2007)
e.g. Morbidelli & Crida (2007)

Walsh et al 2011,2012
Giant planet formation scatters planetesimals

e.g. Kretke et al in prep, Raymond & Izidoro 2017
Conclusions

- Growth to ~mm to cm sized particles should be relatively efficient, but then growth stalls

- These “pebbles” can be collected to form planetesimals, and later accreted to form planets
  - This likely implies wide scale mixing of small particles, is this consistent with constraints?

- The mass of proto-terrestrial planets (while the gas is around) is limited either by the initial planetesimals or the pebble flux

- Planet migration clearly happens sometimes, but it doesn’t appear to always happen