Terrestrial planet formation at home and abroad

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Image credit: NASA/Ames/JPL-Caltech
“Terrestrial” planets

Stages of Planet Formation

- **Grains**
- **Planetesimals**
- **Planetary Embryos**
- **Gaseous Planets**
- **Terrestrial Planets**

**Type 1 migration**

- While gas remains

**Type 2 migration**

**Dynamical instabilities**

**No more gas**

**INFLUENCE**
2 ways to form planetary embryos
From km-sized planetesimals

- $dM/dt \sim M^{4/3}$: runaway growth (Greenberg et al. 1978; Wetherill & Stewart 1989)

From cm- to dm-sized pebbles

- \( \frac{dM}{dt} \sim M^2 \): super-runaway growth \((\text{Lambrechts \\ & Johansen 2012; Morbidelli \\ & Nesvorny 2012})\)

- \( \frac{dM}{dt} \sim M \) then \( M^{2/3} \): oligarchic regime

Late-stage accretion
Raymond, Quinn & Lunine 2006, Icarus, 183, 265
• Planets’ feeding zones widen and move outward in time

• Impacts are smaller early on, biggest impacts happen late

Raymond, Quinn & Lunine 2006, Icarus, 183, 265
Key factors in outcome

- **Disk properties: mass, surface density profile** (Chambers & Cassen 2002; Raymond et al 2005, 2007; Kokubo et al 2006)

- **Degree of eccentricity excitation** (Levison & Agnor 2003; Raymond et al 2009)
Abroad

Terrestrial planet formation in Extrasolar Systems
I. Hot Super Earths

- Exist around 30-50% of MS stars (Mayor et al 2011; Howard et al 2010, 2012; Fressin et al 2013)

- Multiple systems (e.g., Lovis et al 2011; Lissauer et al 2011)

- Compact, non-resonant orbits (Lissauer et al 2011b)

See talk by D. Fischer

A. In situ accretion

Late-stage accretion from massive inner disks (Raymond et al 2008; Hansen & Murray 2012, 2013)

B. Type I migration

- Migration can be inwards or outwards; inwards for embryos (e.g., Kley & Crida 2008; Baade et al 2010, 2011; Bitsch et al 2013)

- Planetary embryos migrate inward in cohorts, form planets in resonant chains (Terquem & Papaloizou 2007; Cresswell & Nelson 2008; Ogihara & Ida 2009)

See talk by A. Crida, poster by Hands & Alexander

II. Giant exoplanets

exoplanets.org; Wright et al 2011, PASP, 123, 412
II. Giant exoplanets

- **Type 2 Migration** (e.g., Lin et al 1996; Armitage 2007)

- **Planet-planet scattering** (e.g., Juric & Tremaine 2008; Chatterjee et al 2008)

See talks by A. Crida, M. Davies

credit: Phil Armitage
At Home

Formation of the inner Solar System
Constraints

- Masses, orbits of terrestrial planets
- Very low eccentricities
- Structure of asteroid belt
- Separation of S, C types  
  
  (Gradie & Tedesco 1982)
- Accretion timescales from Hf/W
  - Earth: 50-100 Myr  
  
  (Touboul et al 2007; Kleine et al 2009)
  - Mars: few Myr  
  
  (Nimmo & Kleine 2007; Dauphas & Pourmand 2011)
- Water delivery to Earth
  - Asteroidal source explains D/H  
  
  (Morbidelli et al 2000, Marty & Yokochi 2006)
“Classical model” for terrestrial planet formation

- Jupiter, Saturn formed on current orbits (or close to them) and sculpted late stage terrestrial accretion
What were Jupiter and Saturn’s orbits at early times?

- Nice model: Jup and Sat had lower eccentricities, in 3:2 resonance
- Current orbital radii, higher eccentricities
Gas giants on current orbits but with $e=0.1$

Raymond et al 2009, Icarus, 203, 644
Jup, Sat in resonance \( e_{\text{Jup}} \approx e_{\text{Sat}} \approx 0.1 \)

The Mars problem

Earth forms dry

Inconsistent with late migration of giant planets

A possible solution to the Mars problem
(Hansen 2009; also Wetherill 1978; Chambers 2001)

- A small Mars forms naturally if inner disk is only from 0.7-1 AU
- An edge effect

Jupiter in the gaseous disk

- Semi major axis
- Time

- ~50 M_{\text{Earth}}
- Type II migration starting
- ~200 M_{\text{Earth}}

slide by Kevin Walsh
Jupiter and Saturn in the gaseous disk

- Semi-major axis

- Time

- Fast Migration

- Capture in Resonance

- \(~50\ \text{M}_{\text{Earth}}\)
Jupiter and Saturn in the gaseous disk

- Time
- Semi major axis

- Jupiter and Saturn in the gaseous disk slide by Kevin Walsh
- Capture in Resonance
- Gas disk starts to dissipate

See talk by A. Crida

Masset & Snellgrove 2001; Morbidelli & Crida 2007; Pierens & Nelson 2008; Pierens & Raymond 2011
The “Grand Tack” model

Walsh, Morbidelli, Raymond, O’Brien, Mandell 2011, Nature, 475, 206
The Grand Tack

Walsh et al 2011, Nature, 475, 206
Water delivered to Earth by same population that was implanted into asteroid belt as C types (O’Brien et al 2013, submitted)

See poster by S. Jacobson et al.
The terrestrial planets

Summary

• Embryos from planetesimals or pebbles
• Hot Super Earths by in situ accretion or type 1 migration
• Giant exoplanets shake up terrestrial accretion
• “Classical” accretion model: Mars problem
• Grand Tack model makes a small Mars
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