Grain growth and dust trapping in circumstellar disks

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Outline

- The role of dust growth in planet formation.
- Dust collisions: laboratory & numerical experiments.
- Dust evolution models: the radial drift barrier.
- Pressure traps as a solution of the radial drift problem.
- Example of pressure traps:
  - Multiple rings (HLTau)
  - Rings and asymmetries in transition disks
- Take-away messages
Dust growth in planet formation

Protoplanetary disks
Birthsides of planets
Dust growth in planet formation

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Preferential regions where dust can continue growing to planetesimals

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DUST EVOLUTION IN CIRCUMSTELLAR DISKS

Laboratory and Numerical Experiments
Dust Evolution Models
What we know about dust collisions?

Laboratory Experiments
- Stick
- Fragment
- Bounce
- Transfer mass

Numerical Simulations
e.g. Paszun & Dominik (2009)

Collisions with ice monomers at 8m/s
Collisions with silicate monomers at 2m/s

The lack of ice mantles in dust particles decreases the sticking efficiency between grains

\[ v_{\text{frag}}^\text{ice} = 10 - 50 \text{ m/s} \]
\[ v_{\text{frag}}^\text{silicates} = 1 - 5 \text{ m/s} \]
What we know about dust transport?

Settling to the midplane

\[ \Delta v_{sett} \propto \frac{\Omega_k^2 z}{\rho_g c_s} \]

Turbulent mixing

\[ \Delta v_{turb} \propto \sqrt{\alpha_{turb} c_s} \]

Brownian motion (small grains)

\[ \Delta v_{Brownian} = \sqrt{\frac{8k_BT}{\pi}} \times \frac{m_1 + m_2}{m_1 m_2} \]

Coupling and decoupling to turbulent eddies

(Ormel & Cuzzi 2007)

Radial drift
Radial Drift

Equation of motion for the gas:
\[ \vec{f}_{\text{gravity}} + \vec{f}_{\text{centrifugal}} + \vec{f}_{\text{pressure}} = 0 \]

\[ v_\phi^2 = v_{\text{Kepler}}^2 + c_s^2 \frac{d \ln P}{d \ln r} \]

Gas moves with sub-Keplerian velocity

Equation of motion for the dust:
\[ \vec{f}_{\text{gravity}} + \vec{f}_{\text{centrifugal}} \neq 0 \]
\[ \vec{f}_{\text{gravity}} + \vec{f}_{\text{centrifugal}} + \vec{f}_{\text{drag}} = 0 \]

Dust moves towards the higher \( P_{\text{gas}} \)

e.g. Weidenschilling (1977)

Dust Radial Velocities

\[ v_{\text{dust}} = \frac{v_{\text{gas}}}{1 + St^2} + \eta \frac{v_{\text{Kepler}}}{St + St^{-1}} \]

\[ \eta = \frac{1}{\rho r \Omega^2} \frac{dP}{dr} \]

\[ St \propto \frac{a \rho_s}{\Sigma} \]

Brauer et al. (2008)
Dust evolution models: transport and growth

The velocity before particles fragment is set in the models to $\sim 10\text{m/s}$ (average for particles with ice mantles).

The diagram illustrates the relationship between particle size and radial drift, with color coding indicating the logarithm of the gravitational acceleration. The solid white line represents the condition $St \propto \frac{a \rho_s}{\Sigma} = 1$ from Birnstiel et al. (2010).

Key processes:
- **Growth**
  - Sticking
  - Erosion
  - Fragmentation
- **Transport**
  - Radial Drift
  - Settling
  - Turbulent mixing
Evidence of mm-grains in PPD

$K \propto \nu^\beta$

$F_v \propto \nu^{\beta+2} \propto \nu^{\alpha_{mm}}$

If $\beta \leq 1$ ($\alpha_{mm} < 3$), dust grain have grown to millimeter sizes

**Observations:** Ricci et al. (2010)

**Models:** Birnstiel et al. (2010b)

mm-sized pebbles survive despite the fast inward drift and possible fragmentation
Pressure bumps:  
Possible solution for the drift barrier

\[ v_{\phi, \text{gas}}^2 = v_{\text{Kepler}}^2 + c_s^2 \frac{d \ln P}{d \ln r} \]

Example of pressure bumps in disks:
- Edge of a dead zone (regions of low ionization rate, e.g. Dzyurkevich et al. 2010)
- MRI instabilities (e.g. zonal flows, Uribe et al. 2011)
- Spiral arms in self-gravitating disks (e.g. Lodato & Rice 2004, Dipierro et al. 2015)
- Outer edge of a planet-carved gap (e.g. Pinilla et al. 2012b, Zhu et al., 2012)
Particle trapping by zonal flows

Several regions where the gas is super-Keplerian

$\frac{(v_{\phi}^2 - v_k^2)}{v_k}$

$-0.20 \rightarrow -0.020$

3 4 5 6 7 8

Radius

Pressure bumps of 25-30% of amplitude allow to reduce radial drift and keep millimeter particles in the outer regions of disks

See also Dittrich et al. (2013); Simon & Armitage (2014)
The observed rings in HLTau can originate from particle trapping in pressure bumps. These bumps naturally arise in simulations that include magnetic fields.
Trapping induced by embedded planets in disks

At the outer edge of a planet carved-gap, the pressure gradient is positive and particles can be trapped.

Solid white line: \[ St \propto \frac{ap_s}{\Sigma} = 1 \]

Credit: P. Armitage
Ring-like structure in transition disks

Transition disk structures appear to support the presence of unseen planets or companions in protoplanetary disks.
HD100546: two ring-like emission

ALMA-Cycle 0, Walsh et al. (2014)

Large dust grains are significantly more centrally concentrated than molecular gas

Ring of dust external to the proposed protoplanet at 70 AU (Quanz et al. 2013, 2015, Currie et al. 2015)
Sequential planet formation in HD 100546

The two-ring like emission is consistent with tapping by two companions. If the outer companion is massive, it must be younger (2.5-3 Myr) than the inner companion, to trap the right amount of dust.

Pinilla et al. (in press)

Talk in FM 1 (Wed 12 August)
No only radial trapping can happen
Azimuthal trapping too $\rightarrow$ Vortices

Velocity difference across the interface between two fluids
Rossby wave instability or Kelvin–Helmholtz instability in rotating disks

Example: coffee and cream

In a disk, they can form:

- Active/Dead boundary zone (e.g. Lyra & Mac Low, 2012, Regaly et al., 2012, Flock et al, 2014)
- At the edge of planet gap (e.g. Ataiee et al, 2013, Zhu & Stone 2014)
Vortices efficiently trap particles

**Vortex at the outer edge of gap**

Ataiee et al., 2013

**IRS 48**

**ALMA Cycle 2**
(Band 9 -450 µm)

**VLA**
(9 mm)

van der Marel et al.
(accepted to ApJL)

Vortices can create high-contrast asymmetries. Larger grains are expected to be more azimuthally concentrated than smaller particles.

But not all the observed asymmetries are vortices. Stay tuned for SR21 and HD 135344B cases (Pinilla et al., in rev)
Take-away messages

1. Rapid radial drift is a problem that affects all disks. Pressure traps should be a common phenomena in circumstellar disks.

2. Particle trapping can create single or multiple ring structures. Example: HLTau (magnetic pressure bumps), LkCa15, HD 100546 (embedded planets)

3. Vortices efficiently trap particles in the azimuthal direction, creating high-contrast asymmetries. Example: IRS 48