Dust evolution in protoplanetary disks

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Outline of the talk

1. Basic information about the protoplanetary disks
2. Dust evolution
3. Computational methods
4. Growth barriers
5. Possible scenarios of planetesimal formation
Protoplanetary disks

Dullemond+ 2006
Protoplanetary disks

- Typical mass: \( \sim 0.01 \, M_\odot \)
- Typical size: \( \sim 100 \, \text{AU} \)
- Typical lifetime: \( \sim 5 \, \text{Myrs} \)
- Dust-to-gas ratio (from the ISM): \( \sim 0.01 \)
- Constraints from the Solar System: Minimum Mass Solar Nebula \( \Sigma_{\text{gas}} \propto 1700 \times r^{-1.5} \, \text{g/cm}^2 \) (but observations indicate shallower profile!)
Protoplanetary disks

Radial force balance:

\[
\frac{v_{\varphi, \text{gas}}^2}{r} = \frac{G M \ast}{r^2} + \frac{1}{\rho} \frac{d P}{d r}
\]

\[
v_{\varphi, \text{gas}} = v_K \sqrt{1 + 2 \eta}, \quad \eta \propto \frac{d P}{d r} < 0
\]

Gas is sub-Keplerian!
Dust evolution: key processes

Systematic drift:
1. Radial
2. Vertical (settling)
3. Azimuthal

Random motion:
4. Brownian motion
5. Turbulence

\[ \text{St} = \frac{t_s}{t_K} \]

All the processes are described by the Stokes number

Coagulation is inseparably linked to the transport processes
Collision speeds

- Brownian motion
- Turbulence
- Radial drift
- Azimuthal drift
- Vertical settling
- All sources

[Graph showing collision speeds across different grain sizes and environments]
Computational methods for dust evolution

Difficulties in dust modeling:

- Size range: μm to 1000 km (12 orders of magnitude in size or 36 in mass)
- Distance range: mean free path to disk size (~15 orders of magnitude)
- Time range: time between collisions to lifetime of the disk (~13 orders of magnitude)
- Gas disk evolution (+ feedback from dust)
- Composition and internal structure of dust grains

Possible simplifications:

- Analytic model for gas disk (often steady-state)
- Local simulations (but drift timescale ≈ coagulation timescale)
- Vertically integrated and axisymmetric models
- Single material (usually silicates or ice)
- Compact grains or simple prescription for porosity
Computational methods for dust evolution

Monte Carlo algorithms

Smoluchowski equation solvers

\[ \frac{\partial f(m)}{\partial t} = -f(m) \int K(m,m') f(m') \, dm' + \frac{1}{2} \int K(m-m',m') f(m-m') f(m') \, dm' \]
Computational methods for dust evolution

Monte Carlo algorithms

- are straightforward to develop to further spatial dimensions (Zsom+ 2011, Drążkowska+ 2013)
- easy to implement additional particle properties, such as porosity (Zsom & Dullemond 2008; Zsom+ 2010)
- cannot model evolution over long timescales as every collision is resolved
- experience no numerical diffusion of the mass distribution function
- have difficulty resolving features that include low fraction of total mass (but see Ormel & Spaans 2008)
- can be used along with hydrodynamic grid codes (Johansen+ 2012)

Smoluchowski equation solvers

- are capable of simulating dust evolution over long timescales
- resolve equilibrium states well (Birnstiel et al. 2010)
- have a very high dynamical range
- are slowed by a factor of $O(n^3)$, where $n$ is the number of mass bins, for each additional dust property beyond mass (but see Okuzumi+ 2009)
- suffer from high numerical diffusion that affects growth timescale and can lead to unphysical results

Drążkowska+ 2014
Growth barriers

**collisional**
- fragmentation: cm- to m-size

**radial drift**
- drift: m-size at 1 AU, mm-size at 100 AU
- bouncing: mm- to cm-size
Map of the growth barriers

Birnstiel+ 2012
Ideas facilitating planetesimal formation

Pressure bumps

Sweep-up growth

Streaming instability

Whipple 1972
Pressure bump

see also Drążkowska+ 2013

Planetesimal formation is local

Brauer+ 2008
Sweep-up growth triggered by the impact velocity distribution
Planetesimal formation is local and happens only inside of 1 AU! Only ~4% of dust is turned to planetesimals.

Drążkowska, Windmark, & Okuzumi 2014
IAU S310 proceedings
Streaming instability

Johansen et al. 2011

Kowalik et al. 2013

Bai & Stone 2010
Previous SI models: heavy hydrodynamical simulations with restricted size distributions
Planetesimal formation is only possible outside the snow line (due to the bouncing barrier).
It does never happen that 100% of dust is turned to planetesimals.
This picture is very different from what is used as the working hypothesis for planetesimal accretion and planet population synthesis models!
Summary

• Dust evolution modeling is challenging and many simplifying assumptions are used in state-of-the-art models

• Interaction between dust and gas leads to redistribution of solids (constant dust to gas ratio becomes wrong quickly)

• Planet formation is hindered by the growth barriers

• Planetesimals may not be formed everywhere in the disk