DUST GRAIN EVOLUTION

— FROM SUB-MICRON GRAINS TO PEBBLES TO PLANETESIMALS —

Myriam Benisty & Til Birnstiel
Sagan Exoplanet Summer Virtual Workshop

Credit: ESO/L. Calçada
Why care about solids?

Dust ...

... is the **planet forming** material

... is surface area for **chemistry** & means of **transportation**

... affects temperature/ionization → **MHD/chemistry**

... is by far the dominant opacity → **observations**
Outline – Part 1

1. Dust Dynamics
2. Dust Growth
3. Dynamics + Growth
4. Planetesimal Formation

Follow-up talks

Observations → Myriam Benisty
Structure Formation → Jaehan Bae

Gives more citations or relevant key words to look into. Will be skipped in the talk.

In depth

Gives estimates, time scales, or rules-of-thumb that are good for back-of-the-envelope calculations.
Dust Dynamics
Dust Evolution

Solids & Gas Evolve **Differently**
But Not **Independently**!

https://youtu.be/p_f6lWWc9jQ
Drag Forces

Epstein Drag Regime: if particle size ≲ gas mean free path

\[ \vec{F}_{\text{drag}} = - \frac{4\pi}{3} \rho_g a^2 v_{\text{th}} \vec{v} \]

Inner disk: Stokes drag can become relevant: if particle size > gas m.f.p.:

\[ \vec{F}_{\text{drag}} = - \frac{C_D}{2} \pi a^2 \rho_g v \vec{v} \]

- $a$: grain radius
- $v_{\text{th}}$: mean thermal speed
- $C_D$: drag coefficient
- $v$: dust-gas rel. velocity
- $\rho_g$: gas volume density
Estimate the time scale of adapting to the gas speed:

$$t_{\text{stop}} = \frac{v}{\ddot{v}} = \frac{mv}{F_{\text{drag}}} = \frac{\rho_s a}{\rho_g v_{\text{th}}}$$

Example at 1 au:
- 1 µm: 4 s
- 1 m: 0.2 yr

More useful: Stokes number – the "aerodynamic size":

$$St = t_{\text{stop}} \Omega = \frac{a \rho_s \pi}{\Sigma_g 2}$$

- $St \ll 1$: coupling faster than 1 orbit
- $St \gg 1$: coupling longer than 1 orbit
Radial Drift

Solids

Keplerian velocity

gravitational force

-centrifugal force

gas $v^2 \frac{G M_*}{r^2} + \frac{1}{\rho} \frac{dP}{dr}$

Gas

sub-Keplerian velocity

gravitational force

-centrifugal force & pressure force

gas $v_{\phi,\text{gas}} = v_K \sqrt{1 - \frac{\gamma_p}{\rho} \left(\frac{h}{r}\right)^2}$

typically ~ 0.1% slower than Kepler
Radial drift

1. Large grains (= pebbles = "St \gtrsim \alpha") drift to higher pressure.

2. \( v_{\text{drift}} \propto St \propto \text{particle size} \)

Quick Estimate

- 80 mph
- 130 km/h
Vertical Settling

Large grains \((St \gtrsim \alpha)\) sediment

\[
\dot{z} = -z \Omega_k^2 \quad \frac{\dot{z}}{t_s} \quad \text{damping}
\]

\[
v_{\text{settling}} = -z \Omega^2 t_s
\]

\[
t_{\text{set}} \sim \frac{1}{St \Omega}
\]

Quick Estimate

In depth

(e.g. Fromang & Nelson 2009 + refs. Inside)
Turbulence mixes the solids in all directions!

This animation shows the Vertical Shear Instability (VSI) mixing a tracer fluid, a recently (re-)discovered instability that might drive turbulence in disks.

see: Nelson et al. 2013
Stoll & Kley 2016 (this video) and others
Diffusion acts on the diffusion time scale

\[ t_{\text{diff}} \sim \frac{\text{length scale}^2}{\text{Diffusion coefficient}} \]

which in our case works out to

\[ t_{\text{diff}} = \frac{1}{\alpha \Omega} \]

Quick Estimate
Settling vs. Mixing shows sets dust scale height of
dust scale height of

\[ h_{\text{dust}} \approx h_{\text{gas}} \sqrt{\frac{\alpha}{\text{St} + \alpha}} \]

The value \( \frac{\text{St}}{\alpha} \) also determines radial and azimuthal trapping.

Quick Estimate

Radial: Dullemond et al. 2018
Azimuthal: Birnstiel et al. 2013, Lyra & Lin 2013
... and references therein
Vertical Mixing & Drift
Vertical Mixing & Drift

large grains: well coupled/mixed
small grains: sediment

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Vertical Mixing & Drift

- **Small grains:** well coupled/mixed
- **Large grains:** drift up the pressure gradient
Vertical Mixing & Drift

- **large grains:**
  - Drift up the pressure gradient
  - Drift with the sediment
- **small grains:**
  - Well coupled/mixed
Vertical Mixing & Drift

large grains: drift up the pressure gradient

small grains: well coupled/mixed
Dust Growth
Collisional Effects

Movies courtesy of Blum group
e.g. Blum et al. 2014
Transport ↔ Collisions

Changes Environments
Drives Collision Speeds
Size Sorting

Dust Transport

Affects cross section & Charges
Aerodynamic properties

Dust Composition / Structure

Sets cross section
Aerodynamic properties

Size Evolution

Impact speed environment

collision rate

collision outcome
Despite all these complications:

\[ t_{\text{grow}} \sim \frac{1}{\epsilon \Omega} \]

(size doubling time scale) works surprisingly well

**Quick Estimate**

This estimate assumes turbulent velocities to dominate. Derivation in

Brauer et al. 2008
Birnstiel et al. 2012

**In Depth**

\[ \epsilon \quad \text{dust-to-gas ratio} = \frac{\Sigma_d}{\Sigma_g} \]
Dust Growth + Dynamics
Size matters! $\Rightarrow$ Size evolution matters!

**fixed size**

**evolving size**

Movies by J. Drążkowska with DUSTPY code (Stammler & Birnstiel in prep.)
Size matters! ⇒ Size evolution matters!

**fixed size**

**evolving size**

Movies by J. Drążkowska with DUSTPY code (Stammler & Birnstiel in prep.)
Dust Evolution in a Nutshell

Particle size

\[
t_{\text{grow}} \sim \frac{1}{\epsilon \Omega}
\]

growth slower outside

Distance from Star
Dust Evolution in a Nutshell

Distance from Star

Particle size

1 au
100 au

\( v_{\text{drift}} \propto a \)

large particles drift faster
Drift limit $\equiv t_{\text{grow}} = t_{\text{drift}}$

Birnstiel et al. 2012
Dust Evolution in a Nutshell

Birnstiel et al. 2012

Distance from Star

Particle size

μm

cm

m

1 au

100 au

Δν ∝ a

large particles collide faster

fragmentation limit

drift limit
Dust Evolution in a Nutshell

Distance from Star

Particle size

\[ \Delta v \propto a \]

\[ \Delta v > v_{\text{frag}} \rightarrow \text{fragmentation} \]

Birnstiel et al. 2012
Dust Evolution in a Nutshell

Particle size

m

1 au

100 au

Distance from Star

Birnstiel et al. 2011, 2015
Dust Evolution in a Nutshell

Distance from Star

Particle size

µm

cm

m

1 au
100 au

Birnstiel et al. 2011, 2015
Dust Evolution in a Nutshell

Particle size

Distance from Star

Birnstiel et al. 2011, 2015
Dust Evolution in a Nutshell

Birnstiel et al. 2012
PLANETESIMAL FORMATION
→ All particles drift onto the star
→ No planetesimals are formed
→ There shouldn’t be any planets
Some **collisional pathways** have been suggested:
- "lucky particles":
  e.g. Windmark et al. 2012
  too inefficient
- "porous growth":
  e.g. Kataoka et al. 2013
  inner disk only, porosity too high?

In Depth
Gravoturbulent Planetesimal Formation

Requires:
- "large" particles
- dust overdensities (~3% instead of 1%)

see also: Youdin & Goodman 2005, Bai & Stone 2010 and others
Gravoturbulent Planetesimal Formation

log(\(\Sigma_p/\Sigma_P\))\textsuperscript{Nesvorny et al. 2019}

Requires:  
- "large" particles
- dust overdensities (~3% instead of 1%)

see also: Youdin & Goodman 2005, Johansen et al. 2007, Bai & Stone 2010 and others
Gravoturbulent Planetesimal Formation

Nesvorny et al. 2019

Observations: Trans-Neptunian Objects
Simulation of Streaming Instability

SI explains fraction of binary objects & their size range!
Not all is good!

Recent issues:
the streaming instability might not work if

- external turbulence is present:
  Auffinger & Laibe 2018
  Umurhan et al. 2020
  Gole et al. 2020
  Klahr & Schreiber 2021

- particles not of single sizes
  Krapp et al. 2019
  Zhu & Yang 2021
  Paardekooper et al. 2020
| Growing planetesimals is hard  
(bouncing, fragmentation, drift) | Collapsing small dust is impossible  
(small grains coupled to gas) |
|--------------------------------|----------------------------------|
| Growing pebbles is easy  
(up to one of the growth barriers) | Collapsing pebbles is easy  
*if dust is accumulated* |

**Dust Evolution +**  
**Convective Overstability**  
**GSF Instability**  
**Rossby Vortices**  

...  
Dead Zone Edge  
Zonal Flows  
...  

= Planetesimals
What causes the trapping?

See talk by Jaehan Bae

Andrews et al. 2020
Snow Lines: Complicated

Particles drift inward (to higher pressure)

dust temperature

hotter →

gas density
denser →

large grains
Snow Lines: Complicated

- Dust temperature:
  - hotter →

- Gas density:
  - denser →

- Inside water snow line: water sublimates

- Large grains
Snow Lines: Complicated

Particles without water break up easily.

dust temperature

hotter →

gas density
denser →

large grains
Snow Lines: Complicated

dust temperature

gas density

denser →

denser →

hotter →

smaller grains drift slower
→ traffic jam

large grains

small grains
Snow Lines: Complicated

- hotter $\rightarrow$ smaller grains drift slower $\rightarrow$ traffic jam
- denser $\rightarrow$ larger grains
- dust temperature

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Snow Lines: Complicated

Idea:
Birnstiel et al. 2010

Follow ups:
Banzatti et al. 2015
Drazkowska et al. 2017
Lichtenberg et al. 2020
...

Recent issues: depends on microphysics
Gundlach et al. 2018
Steinpilz et al. 2019
Musiolik & Wurm 2019

Snow lines are complicated ...

... by microphysics like opacities, evaporation, recondensation, mixing, grain growth & fragmentation, shadowing, ...

In Depth

gas density
denser →
dust temperature
hotter →
large grains
small grains

large
gas density
denser →
dust temperature
hotter →
large grains
small grains

In Depth
... slower in the outer disk
... faster in higher dust-to-gas ratio
... until they don't stick (but bounce/fragment)
... depending on microphysics

Dust Particles grow ...

... drift faster if they are larger
... are diffused by turbulence
... form planetesimals if $St$ & $\epsilon$ large enough

Dust Particles ...

... now it's time for a reality check!
→ Observations
Outline – Part 2

1. Observations of dust grains
2. Evidence for dust growth
3. Evidence for dust trapping
4. Evidence for dust dynamics
Dust observations

Observations

\[
\begin{align*}
\kappa [\text{cm}^2/\text{g}] & \quad \lambda [\text{mm}] \\
\text{a}_{\text{max}} = 1\mu\text{m} & \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^0 \quad 10^1 \quad 10^2 \\
\text{a}_{\text{max}} = 10\mu\text{m} & \\
\text{a}_{\text{max}} = 100\mu\text{m} & \\
\text{a}_{\text{max}} = 1\text{mm} & \\
\text{a}_{\text{max}} = 1\text{cm} & \\
\end{align*}
\]

Birnstiel et al. 2018
Dust observations

Multi wavelength analysis:
- Probe different regions
- Probe different dust sizes
- Constrain dynamical processes
Evidence for grain growth

- Spectral slope gives $a_{\text{max}}$
- A low spectral index could be due to high optical depth regions

In the optically thin regime

$$F(\nu) \propto M_{\text{dust}} \cdot \nu^{2+\beta}$$

$$\kappa(\nu) \propto \nu^\beta$$

Maximum dust size

$$B_\nu \propto \nu^2$$

If $\beta < 1$ (or $\alpha < 3$):
- large dust grains

In the optically thick regime

$$F(\nu) \propto B_\nu(T) \cdot \text{Disk Area}$$

Andrews et al. 2020
Spectral index

Flux density

Wavelength

© Tazzari

Tazzari et al. 2021a

Ansdell et al. 2016, 2018

© Tazzari

Tazzari et al. 2021a

0.88 mm

1.3 mm

3 mm
Evidence for grain growth

Pebbles (mm) are found in disks
Optically thin regions require grain growth
Pebbles survive the fast inward drift and fragmentation
Require the presence of dust traps

Tazzari et al. 2021a

Tazzari et al. 2021b
Substructures in dust

Andrews et al. 2018
Evidence for dust trapping

- Rings properties consistent with dust trapping
- Almost constant optical depth possibly indicating planetesimal formation
Evidence for growth in dust traps

- Rings observed at various wavelengths
- Dust surface density and $a_{\text{max}}$ constrained
- Traffic jam and dust traps can be identified

Sierra et al. 2021
Dust dynamics

Avenhaus et al. 2018 Andrews et al. 2018

Scattered light Sub-millimeter continuum
Dust radial drift

- Disk extents in CO and continuum indicate radial drift
- Require dust traps

Andrews et al. 2020

Sanchis et al. 2021

Facchini et al. 2019
Dust radial drift

Most transition disks show small dust grains within their mm-cavities.
Can be used to constrain the pressure gradient.

- Kurtovic et al. in prep
- Garufi et al. 2016
- Villenave et al. 2019
- De Juan Ovelar et al. 2013
Dust vertical settling

- Symmetric gap widths indicate a geometrically thin, settled, disk
- SED requires small dust grains at high altitudes

Pinte et al. 2018
Dust vertical settling

- Effective size-selective vertical settling
- Dust height ~ 1 au at 100 au
- Constrain low turbulence parameter
Conclusions

• **What works?**
  • Dust grains grow and drift to regions of high pressure
  • Pressure bumps are dust traps where grains grow

• **What is missing?**
  • Direct observations of planetesimals in disks is not possible
  • Dust grain sizes are still challenging to measure
  • Porosity is poorly understood
  • Connecting dust growth observed at various stages
  • A global modelling of multiple dust tracers
Coherent understanding on disk evolution

Dust grains of different sizes provide complementary tracers to understand the dynamical processes affecting the disk evolution.

Boccaletti et al. 2020
Tang et al. 2017
Dong et al. 2016
Stolker et al. 2016
Cazzoletti et al. 2018