The impact and origin of dust gaps in planet-forming disks

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Protoplanetary disks

- Distances ~ 100-200 pc
- Sizes ~ 100 au/1 arcsec
- Ages ~ 1-10 Myr

Need for subarcsec resolution…

Testi et al. 2015
Pre-ALMA disk observations

Typical resolution ~0.5-0.8"

ALMA disk observations

Enormous diversity of large-scale dust structures!

Typical resolution ~0.05-0.1"

ALMA et al. 2015; Andrews et al. 2016, 2018; Boehler et al. 2017; Cazzoletti et al. 2018; Dong et al. 2018; Fedele et al. 2017; Isella et al. 2016; Perez et al. 2019; Van der Marel et al. 2013, 2016a & 2020
How it started: transition disks

Typical resolution ~0.25”

Casassus et al. 2013
Zhang et al. 2014
Van der Marel et al. 2013, 2015, 2016
...and how it’s going

Typical resolution ~0.1"
..and (again) how it started:

Typical resolution \(\sim 0.05''\)
...and how it’s going

Typical resolution ~0.035”

=> What’s the origin of dust gaps and rings?

Andres et al. 2018
Dust evolution

- Gas disk has a pressure gradient \( \frac{dp}{dr} < 0 \)
  - Radial inward drift dust
- Large particles move towards high pressure

=> Need pressure bump to prevent radial drift

Weidenschilling 1977
Dust evolution: trapping

- Pressure bump in outer disk
  => through drag forces, large dust gets trapped

=> Rings (gap edges) are pressure bumps!
Dust evolution: trapping

- What is the origin of the azimuthal asymmetries?
- Pressure bump develops Rossby Wave instability*  
  => form long-lived vortices  
  => azimuthal trapping  
  => dust asymmetry

*) Kelvin-Helmholtz instability

Barge & Sommeria 1995
Klahr & Henning 1997
Birnstiel et al. 2013
Problem: dust traps require planets?
Why we think it’s planets
PDS70: two planets!

NIR

H-alpha

Continuum

\(^{12}\text{CO}\) emission

Why we think it's planets

Other signatures

Gas gaps in $^{13}$CO

Misaligned inner disks
(shadows in NIR)

Spiral arms in NIR

Van der Marel et al. 2016
Dong et al. 2015, 2016, 2018
Marino et al. 2015
Casassus et al. 2015
Why we think it’s planets

Kinematics

Velocity kinks

Deviations from Keplerian rotation

Warp

Teague et al. 2018
Pinte et al. 2018, 2019
Mayama et al. 2018
Casassus et al. 2015
Why it may not be planets

Problem: exoplanets at wide orbits are rare (few %)
Why it may not be planets

Direct imaging:
(5-13 M$_{\text{Jup}}$ at 10-100 au)

Radial velocity surveys:
(0.1-18 M$_{\text{Jup}}$ at 0.1-20 au)

Nielsen et al. 2019 (GPIES)
Fulton et al. 2021 (CLS)
Why it could still be planets

Gas giant locations

Solution: inward migration, but still not enough giant planets?
Problem: strong bias towards the brightest disks in high-res observations!

What is the bigger picture?
Large ALMA disk surveys

- Snapshot surveys of 1-2 min/source
- Hundreds of disks in SF regions
- Regions of 1-10 Myr old
- Continuum flux provides disk dust mass

=> Statistics of disk dust mass and evolution!

Ansdell et al. 2016, 2018
Barenfeld et al. 2016
Cieza et al. 2018
Disk evolution: mm-dust

Disk dust mass decreases with age

Ansdell et al. 2016, 2017
Cieza et al. 2018
Disk dust mass scales with stellar mass and decrease with age is stronger for low-mass stars.

Ansdell et al. 2016, 2017
Disk evolution: mm-dust

Disk dust size scales with dust mass and decreases with time: radial drift?

Hendler et al. 2020
Andrews et al. 2018
Tazzari et al. 2017, 2021

So is there drift or traps?
Dust evolution: 2 options

Pinilla et al. 2012, 2020
Lambrechts et al. 2014

Minimum mass to halt drift: pebble isolation mass (~10 Me)
Large(st) ALMA survey (collection ~700 disks)

Distribution dust masses as function of age and disk type

Two separate evolutionary pathways: the (large-scale) gapped disks and drift disks

Van der Marel & Mulders 2021
Gapped disks vs exoplanets

Stellar mass dependence in gapped disks: link with giant exoplanets?

Van der Marel & Mulders 2021
Johnson et al. 2010
Mulders 2018
Debris disks (Kuiper belt analogs)

Note: debris disks much fainter but closer

Dust traps progenitors debris disks?

![Graph showing the relationship between $M_{dust}$ and $L_{frac}$ for different disk types.]

- Gapped disks

Michel et al. 2021
Najita et al. 2021

(IR excess)
Dust traps as ice traps?

Evidence for icy inheritance/transport

van der Marel et al. 2021b

Booth et al. 2021a
Dust drift as ice drift?

Icy dust drift can cause CO depletion

- Oberg et al. 2016, McClure 2019, 2020
- Booth & Ilee 2019, Krijt et al. 2020

Excess CO vapor: C/O~1, elevated C/H
Dust drift as ice drift?

Two types of disks: possible explanation for elevated warm H$_2$O in compact disks

Banzatti et al. 2020
Kalyaan et al. 2021
Dust drift as ice drift?

Can we trace chemical effects of transport in (F)IR?

Dust mass outside CO snowline ($M_E$)

Icy dust transport and trap location determines disk chemistry?

Warm trap: low $C_2H$
- Compact disk
  - CO snowsurface
  - high CO abundance
  - weak $C_2H$ emission
- Warm transition disk

Cold trap: high $C_2H$
- Ring disk
  - low CO abundance
  - strong $C_2H$ emission
- Cold transition disk

$C_2H$ detections

Van der Marel et al. 2021c
Disk evolution

Large scatter in $M_{\text{acc}}$: inconsistent with model?

Hartmann 2016
Mulders et al. 2017
Manara et al. 2020
Disk evolution: alpha-disk model

Line width measurements

\[ v_{\text{turb}} < 0.04 \; c_s \]

MRI suppressed by non-ideal MHD effects in disks

MHD-wind model predicts scatter

Disk wind observed in ALMA-CO

Can we trace disk wind in FIR?

Flaherty et al. 2016
Bai & Stone 2013
Booth et al. 2021c
Tabone et al. 2021
What can we learn in unresolved (F)IR?

- Warm molecular/atomic lines surface layers: ice transport?
- Kinematic signatures disk surface/disk wind?
- $\text{H}_2\text{O}$ ice features: ice composition and history
- Grain size distribution in debris disks
- Mineralogy/grain composition (dust processing)

Need for high sensitivity
Summary

- Large-scale dust gaps are likely caused by giant planets, assuming inward migration
- Dust mass evolution can be understood by a combination of drift and trapping
- Dust traps may be the progenitors of debris disks
- Dust transport may set the disk (ice) chemistry
- Disk evolution may be driven by winds
- Many more research to be done!