Accretion and Dust Evolution in the HL Tau Disk

Importance of the Snow Line in Dust Evolution

(H$_2$O) Snow Line

star

silicate

silicate + ice
Importance of the Snow Line in Dust Evolution

- Location where particle stickiness changes
  (particles coated by water ice is sticky. See Wada et al, 2009; Gundlach & Blum 2015)

- Vapor re-condensation
  (Stevenson & Lunine 1988; Ros & Johansen 2013; Schoonenberg & Ormel 2017)

- Piling-up of silicates
  (Saito & Sirono 2011; Ida & Guillot 2011)

- Sintering
  (Sirono 1999,2011a,b; Okuzumi et al. 2016; Sirono & Ueno 2017)
Snow Lines

abundances of major volatiles in comets (Mumma & Charnley 2011)
What are the Origins of the Dust Rings/Gaps?

- Planets? (e.g., Dipierro+15; Kanagawa+15; Jin+16; Bae+17)
- Instabilities? (e.g., Takahashi+14; Lorén-Aguilar+15)
- Condensation near the snow lines? (Zhang+15)
- Sintering near the snow lines? (this work)
Sintering is a grain fusion phenomenon that happens when the temperature is *slightly below* the sublimation/melting temp.:

silica aggregate before sintering

**after sintering** (1473K, 1hr)

Poppe (2003)
Sintered Aggregates are Brittle

(Sirono 1999; Sirono & Ueno 2017)

Example: aggregates of 0.1-µm icy grains, colliding at 20 m/s

disruption at ≥ 50 m/s
(see also Wada et al. 2009)

disruption at ≥ 20 m/s

w/o sintering

w/ sintering
Even minor volatiles (of volume faction ~1%) are able to produce thick necks!
The Sintering Zones

Sirono (2011b); Okuzumi et al. (2016)

Temp. 100 K 50 K 30 K 10 K

sintering zone: where icy aggregates get sintered
(sintering timescale < collision timescale)

snow line: where ice sublimates

star

H₂O NH₃ CO₂ C₂H₆ CH₄ CO
1D Dust Evolution Model with Sintering

Okuzumi et al. (2016)
Consider aggregates of silicates and ices
\((\text{H}_2\text{O}, \text{CO}, \text{CO}_2, \text{CH}_4, \text{C}_2\text{H}_6, \text{NH}_3, \text{H}_2\text{S}; \text{ Mumma} \& \text{Charnley} 2011)\)

\[ v_{\text{frag}} \text{ (normal)} = 50 \text{ m/s} \left( a_{\text{monomer}}/0.1\mu\text{m} \right)^{-5/6} \text{ (Wada et al. 2009)} \]

\[ v_{\text{frag}} \text{ (sintered)} = 20\text{ m/s} \left( a_{\text{monomer}}/0.1\mu\text{m} \right)^{-5/6} \text{ (Sirono \& Ueno, 2017)} \]
$\text{CH}_4$, $\text{CO}_2$, $\text{C}_2\text{H}_6$, $\text{H}_2\text{O}$
Detailed Comparison with HL Tau

The sintering model reproduces:
✓ Positions of major rings (within an accuracy of <30%)
✓ Radial distribution of mm spectral index $\alpha = \frac{\mathrm{dln} I_\nu}{\mathrm{dln} \nu}$
ALMA has revealed that HL Tau’s mm polarization pattern changes drastically with wavelength (Kataoka et al. 2017; Stephens et al. 2017).

One possibility: the size of dust particles producing the polarized emission is \(~ 100 \mu m \ (\sim \lambda/2\pi)\) (Kataoka et al. 2017).

This size is much smaller than expected for sticky H$_2$O particles (\(~ 1\text{mm}...1\text{cm} \text{at} \ 100 \text{au}) \Rightarrow \text{Strong turbulence?}
Weak Turbulence in the HL Tau Disk

Pinte et al. (2016)

The well-defined morphology of the rings indicates that the dust is concentrated at the midplane:

This strongly suggests that disk turbulence is very weak:

\[ \alpha \equiv \frac{D_{\text{diff}}}{c_s H_{\text{gas}}} \approx 10^{-3} \ldots 10^{-4} \text{ in the outer disk} \]

Then why the particles in the outer disk are so small?
Evidence for Non-sticky CO$_2$ Mantle?

- Outside the CO$_2$ snow line, icy grains might be covered by CO$_2$ ice.
- Recent experiments (Musiolik et al. 2016a,b) confirmed that CO$_2$ ice is less sticky than H$_2$O ice.
- Reason: CO$_2$ is non-polar (having zero dipole moment)

Question: Can this effect explain the small particle size in the outer part of the HL Tau disk?
Including the non-stickiness of CO$_2$ Mantle

Snapshot at 1.4 Myr for $\alpha_{\text{diff}} = 10^{-4}$ (Okuzumi & Higuchi, in prep.)

- As expected, particle size of $\sim 0.1$ mm is realized in the outer disk
- If $\alpha_{\text{diff}}$ is low ($\sim 10^{-4}$), dust settling is also realized.
Including the non-stickiness of CO$_2$ Mantle

Okuzumi & Higuchi, in prep.

With CO$_2$ mantle, the dust gap just interior to the CO$_2$ snow line tends to become deep, because the small particles outside the CO$_2$ snow line slowly drift in.
Summary: A Picture of HL Tau form the Snow-Line Scenario

- **H$_2$O**
- **NH$_3$**
- **CO$_2$**
- **C$_2$H$_6$**
- **CH$_4$**
- **CO**

- Dust rings formed through sintering
- Dust rings formed through sintering
- Additional fragmentation caused by CO$_2$ mantle (origin of polarization pattern)

Particles grow efficiently thanks to sticky H$_2$O mantle

⇒ A sweet spot for planetesimal formation via dust coagulation?