Characterization of the dust content in the ring around Sz 91: indications for planetesimal formation?

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Why do we care about Protoplanetary Disks?
Protoplanetary Disk Structure

Different wavelengths (frequencies) trace different regions.

emission lines (e.g., CO)

IR scattered light

(sub-)mm/cm continuum
(+ optically thin lines; e.g., C$^{18}$O)

atmosphere

gas + small dust grains

midplane

gas + larger solids

modified from Andrews et al. (2020)
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Different wavelengths (frequencies) trace different regions.
Radial drift dilemma

Dust particles drift along the pressure gradient

A 1 m body will drift inward in a few hundred years!!

modified from Andrews et al. (2020)
Disk Sub-structures

High-resolution images

sub-mm structures (1.25 mm)

1-10 Myr

Mean age ~1 Myr

DSHARP; Andrews et al. (2018) and ref there in
**Disk Sub-structures**

High-resolution images

**sub-mm** structures (1.25 mm)

DSHARP; Andrews et al. (2018) and ref there in

1-10 Myr

Mean age \(~1\) Myr

Modified from Carrera et al. (2021)
**Disk Sub-structures**

*High-resolution images*

**sub-mm structures (1.25 mm)**

1-10 Myr

Mean age ~1 Myr

Modified from Carrera et al. (2021)

DSHARP; Andrews et al. (2018) and ref there in

**Planetary systems**

| v_drift | Particle trap |
|---------|---------------|

Modified from Carrera et al. (2021)
**Sz 91**

A young Transition Disk in Lupus

- **Lupus III** Molecular cloud
  - ~160 pc (Gaia EDR3)
- \( M_* = 0.58 \, M_\odot \)
- \( \text{Teff} = 3800 \, \text{K}, \, \text{Spt} = \text{M0} \)
- \( M_{\text{dot}} \sim 10^{-8.8} \, M_\odot / \text{yr} \) (Alcalá+2017)

Mauró et al. (2020); Tsukagoshi et al. (2019)

Dynamical clearing by **multiple planets** is the most likely **gap-opening** mechanism in Sz 91

Canovas et al. (2015)
High-resolution ALMA Observations

**Goals**

- **New ALMA observations at 2.1 mm (band 4)** + archival data at **0.9 mm** (band 7) and **1.3 mm** (band 6)

- **Spectral index** of dust emission
  - grain growth

- **Radial analysis** of the (ALMA) SED
  - Including **scattering** effects*
  - Without assuming **any optical depth** value at any wavelength

- **Optical depth, dust surface density, maximum grain size**

* from Sierra et al. (2019) + HL Tau (Carrasco-González et al. 2019)

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Results

High-resolution ALMA Observations

B4, B6, B7 Radial Intensity Profiles

\[ \alpha = 3.34 \]

Maucó et al. (2021)

\( \alpha (0.8-2.7 \text{ mm}) = 3.36 \rightarrow \text{Canovas et al. (2015)} \)
**Results**

High-resolution ALMA Observations

**B4, B6, B7 Radial Intensity Profiles**

| Radius (au) | Normalized Flux |
|-------------|-----------------|
| 0           | 0.0             |
| 20          | 0.2             |
| 40          | 0.4             |
| 60          | 0.6             |
| 80          | 0.8             |
| 100         | 1.0             |
| 120         | 1.2             |
| 140         | 1.2             |
| 160         | 1.0             |
| 180         | 0.8             |
| 200         | 0.6             |
| 220         | 0.4             |

@220 mas (35 au)

\( \alpha = 3.34 \)

**Classical Approach**

\[ \alpha_{\text{thin}} = 2 + \beta_{\kappa} \]

\( 1 \text{ mm} < a_{\text{max}} < 2.5 \text{ mm} \)

\( \alpha(0.8-2.7 \text{ mm}) = 3.36 \rightarrow \) Canovas et al. (2015)

Maucó et al. (2021)
Results

Optical Depth

Dust emission \textbf{NOT} optically thick!

\[ \tau = 0.1 - 0.6 \text{ (with scattering)} \]
\[ \tau = 0.1 - 0.01 \text{ (without scattering)} \]

\textbf{DSHARP} sample
\[ \tau = 0.2 - 0.6 \]
Dullemond+2018

Maucó et al. (2021)
Sz 91

Dust mass & Maximum grain size

Results

\[ a_{\text{max}} = 0.61 \text{ mm} \]

\[ M_{\text{dust}} = 31.3 \, M_{\odot} \]

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**Results**

*Dust mass & Maximum grain size*

**Classical Approach**

\[ a_{\text{max}} = 1-2.5 \text{ mm} \]  
\[ M_{\text{dust}} = 31.3 \ M_\odot \]  

>  

\[ a_{\text{max}} = 0.61 \text{ mm} \]  
\[ M_{\text{dust}} = 8.89 \ M_\odot \]  

Optically thin, no scattering, single dust opacity, single dust temperature

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Results

Mass budget problem for planet formation

Dust mass in protoplanetary disk appears to be **too low** to form the observed exoplanetary systems → assuming **optically thin** emission!

- Classical Approach
- \( a_{\text{max}} = 1-2.5 \text{ mm} \)

Planets form extremely **fast**

\[ M_{\text{dust}} = 31.3 \, M_\odot \]

\[ > \]

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Sz91 in Context: Spectral index

Results

Lupus disk population

\[ \alpha = 3.34 \]

spectral indices and fluxes from Tazzari et al. (2020), Ansdell et al. (2018)

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TD in other regions

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grain size \( \alpha = 3.34 \)

op. thick

spectral indices from Pinilla et al. (2014, 2015, 2019), cavity sizes are taken from Pinilla et al. (2014), Francis & van der Marel et al. (2020), van der Marel et al. (2015), Cieza et al. (2020) and Ribas et al. (2016)

Zhu+2019

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Interpretation

- **Optically thick** disk with scattering
- Dust albedo $\sim 0.9$
  - $a_{\text{max}} = 0.1 - 1 \text{mm}$
- **Spectral index**
  - $\alpha \sim 2$ (thick)
  - $\alpha > 2.5$ (thin)

Zhu et al. (2019)

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*Valid inner disk* ($r < 50\text{ au}$)
*rings modeled with Gaussians profiles*
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Optically thick disk with scattering

Macías et al. (2021)

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*Rings modeled with Gaussians profiles*
**Interpretation**

Stammler et al. (2019)

- 1D-model (Birnstiel+2010)
- dust growth, fragmentation
- Planetesimal formation
  - streaming instability
- 2th ring in HD 163296
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Planetesimal formation

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Interpretation

Planetesimal formation

Spectral index

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Carrera et al. (2021): extremely robust process in protoplanetary disks.
Conclusions

- We obtained 2.1 mm ALMA observations @0.1” resolution
- Well resolved ring of dust peaking at ~90 au from the central star
- By using multi-wavelengths observations we found an almost constant spectral index of $\alpha \approx 3.34$.
- Compare to the disk population of Lupus, Sz 91 has the highest $\alpha$
  - optically thick regions in un-resolved sources may account for the low $\alpha$
- Compare to TDs in other regions, Sz 91 behaves as expected for a TD with a huge cavity.
  - By performing a radial fitting of the ALMA SED we found:
    - optical depths: 0.1 - 0.6 (same as for the DSHARP sample)
    - $a_{\text{max}} \approx 0.61$ mm
    - $M_{\text{dust}} = 31.3 \, M_\odot$

Evidence of grain growth due to accumulation of mm particles in the ring. Possible on-going planetesimal formation in a transition disk.

It remains to be tested if the ring-like accumulations around the dust depleted cavities in transition disks show similar characteristics as the sub-structures of the DSHARP disks.
Thanks!

(Lee)