Observations and Modeling of Circumstellar disks

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Goals & Methods

• **Goal:** Constrain conditions for planet formation
  – Spatial distribution of gas and dust
  – Physical conditions: Temperature, velocity, magnetic field structure

• **Specific questions**
  – Global disk structure = f(time)
  – Small-scale structure,
    e.g., induced by planet-formation or planet-disk interaction

• **Approach**
  – Multi-wavelength observations with spatial resolution of ~0.1AU – 100AU
  – Modeling
Overview

1. General remarks
   a) Multi-wavelength observations
   b) Spatially resolved disk images

2. Exemplary studies
   a) Protoplanetary / Transitional Disks
   b) Debris disks

3. Tracing proto-planets (if time allows)
General remarks

a) Potential of multi-wavelength observations
From dust to planets

Particle size

\[ a \approx \text{Observing wavelength} \]
From dust to planets

- Spectral Energy Distribution
- Scattered light polarization
- Dust emission/absorption features
- Multi-wavelength imaging

Early growth: sticking & coagulation

Particle size $\approx$ Observing wavelength
From dust to planets

Particle size $\approx$ Observing wavelength

Early growth: sticking & coagulation

```
From dust to planets

Early growth: gas sweeping

Total dust mass and Grain size derived from the (sub)mm (slope) of the SED: $F_\nu \sim \kappa_\nu \sim \lambda^{-\beta}$

Underlying assumption: Optically thin disk
```

$log a$
Low-resolution SED / Disk structure

Flaring: Star can illuminate / heat disk more efficiently

[Beckwith, 1999]
Contribution of a possibly remaining circumstellar envelope (Scattering, Reemission, Absorption)

**SED analysis: Ingredients**

CoKu Tau 1  
DG Tau B  
Haro 6-5B  

IRAS 04016+2610  
IRAS 04248+2612  
IRAS 04302+2247  

Young Stellar Disks in Infrared  
HST • NICMOS

PRC99-05a • STScI OPO  
D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA
SED analysis: Ingredients

Contribution of a possibly remaining circumstellar envelope (Scattering, Reemission, Absorption)

Significant foreground extinction + Interstellar polarization (wavelength-dependent)

[ courtesy of R. Launhardt ]
Contribution of a possibly remaining circumstellar envelope (Scattering, Reemission, Absorption)

Significant foreground extinction + Interstellar polarization (wavelength-dependent)

Dust characteristics (absorption/emission)

Prominent Example: ~10um Silicate Feature

8-13micron spectra of 27 T Tauri stars
based on surveys by Przygodda et al. (2003) and Kessler-Silacci et al. (2004) using TIMMI2/3.6m, LWS/Keck

[Schegerer, Wolf, et al., 2006]

Shape of feature =

\[ f(\text{Chemical Composition, Crystallization degree}) \]

\[ \Rightarrow \text{Grain Evolution} \]

\[ \Rightarrow \text{Physical Conditions} \]
Contribution of a possibly remaining circumstellar envelope (Scattering, Reemission, Absorption)

Significant foreground extinction + Interstellar polarization (wavelength-dependent)

Dust characteristics (absorption/emission)

Characteristics of the illuminating/heating sources (stellar photosphere, accretion, single star vs. binary)

**Prominent Example: ~10um Silicate Feature**

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f(Chemical Composition, Crystallization degree)

⇒ Grain Evolution

⇒ Physical Conditions
SED analysis: Conclusions

Proper analysis of multi-wavelength observations require

• **Radiative Transfer Simulations**
  – Detailed numerical modeling taking into account absorption / heating / reemission + scattering processes
  – Our approach: Monte-Carlo Method

• **Proper Fitting Techniques**
  Our approaches
  – Database fitting
  – Simulated annealing (Kirkpatrick et al. 1983)
    • Modification of Metropolis-Hastings algorithm for optimization
    • Implementation independent of problem dimensionality
    • Local optima overcome inherently
SED analysis: Conclusions

http://www.astrophysik.uni-kiel.de/~star

[Wolf et al. 1999; Wolf 2003]
SED analysis: Conclusions

but

SEDs can be well reproduced, but not unambiguously

⇒ Information about spatial brightness distribution required:
  – Spatial disk structure
    (e.g., inner/outer radius, radial scale height distribution)
  – Spatial distribution of Dust parameters (composition, size) and Gas phase composition/excitation

Note:

Appearance of circumstellar disks determined by both, its **Structure** (density distribution) and **Dust properties**
General remarks

b) Spatially resolved images
Requirements – HST, AO, Interferometry
Edge-on disks

Optical/IR

Wavelength-dependence of the apparent vertical extent of the disk

⇒ Vertical opacity structure

⇒ Constraints on grain size in upper disk layers (dust settling?)

Approximate disk size (dust)

Disk flaring
Edge-on disks

(Sub)mm

Wavelength-dependence of the radial brightness distribution

⇒ Radial disk structure

⇒ Radial distribution of dust grain properties; Abundance / Excitation of gas

⇒ Large inner gap?

⇒ Velocity structure (gas)
Face-on disks

Optical / IR

Wavelength-dependence of the radial brightness distribution

⇒ Disk:
  ⇒ Flaring; Surface structure (local scale height variations)

⇒ Dust:
  ⇒ Scattering properties (scattering phase function) in different layers
  ⇒ Chemical composition = f (radial position); e.g., silicate annealing

AB Aurigae - Spiral arm structure
(Herbig Ae star; H band; Fukagawa, 2004)
Face-on disks

(Sub)mm
Radial/azimuthal disk structure

⇒ Asymmetries, Local density enhancements
⇒ Gaps, Inner dust-depleted regions

Exemplary studies

a) Protoplanetary / Transitional disks
IRAS 04302+2247 („Butterfly star“)

- Wavelength-dependence of the dust lane width
- Relative change of the brightness distribution from 1.1μm-2.05μm
- Slight symmetry of the brightest spots

[Padgett et al. 1999]
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[Wolf et al. 2003]
IRAS 04302+2247 („Butterfly star“)

• Conclusion:
  Optically thin (upper) disk layers + envelope dominated by ISM-type grains

• Disk reemission
  – Constraints on disk interior
  – Early measurement with OVRO:

Dust grains with radii up to \(\sim 100\,\mu m\) in the circumstellar disk!

Confirmation of different dust evolution in the shell vs. disk

J band polarization map:
Linear Polarization: **Up to 80%**

[Lucas & Roche 1997]

1.3mm, 600AU x 600AU

[Wolf et al. 2003]
IRAS 04302+2247 („Butterfly star“)

- Verification of the previous analysis

[Wolf et al. 2003, 2008]
IRAS 04302+2247 („Butterfly star“)

IRAM / PdBI: 1.3mm, continuum

IRAS 04302+2247 („Butterfly star“)

IRAM / PdBI: 1.3\,mm, continuum

SMA: 0.89\,mm, continuum + HST/NICMOS

IRAS 04302+2247 („Butterfly star“)

- New observations – Reduction of Degeneracies – New Constraints

[Gräfe, Wolf, et al., in prep.]
IRAS 04302+2247 („Butterfly star“)

- New observations –
  - Reduction of Degeneracies –
  - New Constraints

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**Best Fit**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>$a_{\text{max,ld}}$</td>
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<td>$\alpha$</td>
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<td>$h_{\text{ld}}$</td>
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<td>$M_{\text{ld}}$</td>
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<td>$i$</td>
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<tr>
<td>$\beta$</td>
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<tr>
<td>$r_{\text{out,ld}}$</td>
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<tr>
<td>$M_{\text{sd}}$</td>
<td>0.00065 M$_{\odot}$</td>
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**Constraints**

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<th>Constraint</th>
<th>Value</th>
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<td>$a_{\text{max,ld}}$</td>
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<td>$1.12 &lt; \beta &lt; 1.17$,</td>
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<td>$4.0$ AU $\leq h_{\text{ld}} \leq 7.0$ AU,</td>
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<tr>
<td>$175.0$ AU $\leq r_{\text{out,ld}} \leq 225.0$ AU,</td>
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<tr>
<td>$0.0008$ M$<em>{\odot} \leq M</em>{\text{dust}} \leq 0.001$ M$_{\odot}$,</td>
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<tr>
<td>$i$</td>
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<tr>
<td>$\delta \alpha$</td>
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<tr>
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<td>25.0 AU</td>
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<tr>
<td>$\delta M_{\text{dust}}$</td>
<td>0.0001 M$_{\odot}$</td>
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Observations considered

HST NICMOS NIR imaging

Submm single-dish: SCUBA/JCMT, IRAM 30m

Interferometric mm cont. maps: SMA (1.1mm), OVRO (1.3/2.7mm)

SED, including IRAS, ISO, Spitzer

[Sauter, Wolf et al. 2009]
Main Conclusions

• Dust
  – ISM dust grains in the envelope and „upper“ disk layers
  – Dust grains in the disk midplane only slightly larger than in the ISM

• Disk
  – Inner disk radius: ~ 45 +/- 5 AU

[Sauter, Wolf et al. 2009]
**Observation**
IRAM interferometer, 1.3mm, beam size $\sim 0.4''$

**Results**
Disk of HH30 is truncated at an inner radius $37 \pm 4$ AU

**Interpretation**
- Tidally truncated disk surrounding a binary system (two stars on a low eccentricity, 15 AU semi-major axis orbit)
- Additional support for this interpretation: Jet wiggling due to orbital motion
- The dust opacity index, $\beta \approx 0.4$, indicates the presence of cm size grains (assuming that the disk is optically thin at 1.3mm)

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**Fig. 1.** Superimposition of the PdBI 1.30 mm continuum map on the HST data. The spatial resolution is $0.59 \times 0.32''$ at PA 22°. The center of projection is RA = 04h31m37.469 and Dec = 18°12′24.22" in J2000. Contour levels start at and are spaced by $3\sigma = 0.56$ mJy/beam, corresponding to 68 mK. The registration of the HST image is approximate, as the positions given by Anglada et al. (2007) and Cotera et al. (2001) differ by 1''.

[Guilloteau et al. 2008]
HH30

Resulting inner radius: 50 +/- 10 AU

Fitting of
a) reconstructed map
b) uv data

[Madlener, Wolf, et al., subm.]
HH30

[Based on observations published by Cotera et al. 2001]
HH30

HH 30  PSF Reference

[based on observations published by Cotera et al. 2001]

[Madlener, Wolf, et al., subm.]
HH30

Observations  New Model

[based on observations published by Cotera et al. 2001]  [Madlener, Wolf, et al., subm.]
Spatially resolved millimeter images reveal large inner hole

<table>
<thead>
<tr>
<th>model</th>
<th>A (NIR)</th>
<th>B (SED)</th>
<th>C (SED/mm)</th>
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<tr>
<td>$\eta$</td>
<td>0.019</td>
<td>$0.029^{+0.024}_{-0.005}$</td>
<td>0.03</td>
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<td>$\alpha$</td>
<td>2.45</td>
<td>$2.39^{+0.28}_{-0.23}$</td>
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<tr>
<td>$\beta$</td>
<td>1.09</td>
<td>$1.21^{+0.01}_{-0.13}$</td>
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<tr>
<td>$R_{in}$ [AU]</td>
<td>2.1</td>
<td>$0.27^{+0.98}_{-0.17}$</td>
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</tr>
<tr>
<td>$R_{att}$ [AU]</td>
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<td>$47.1^{+2.7}_{-16.7}$</td>
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<tr>
<td>$R_{out}$ [AU]</td>
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<td>$485^{+15}_{-360}$</td>
<td>175</td>
</tr>
<tr>
<td>$h_{100}$ [AU]</td>
<td>14.8</td>
<td>$14.9^{+0.5}_{-1.4}$</td>
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<td>$m_{dust} [10^{-5} M_\odot]$</td>
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<td>$7.4^{+10.1}_{-2.8}$</td>
<td>5.04</td>
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<tr>
<td>$T_{eff}$ [K]</td>
<td>3300</td>
<td>$3200^{+700}_{-200}$</td>
<td>3300</td>
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<tr>
<td>$L_*$ [$L_\odot$]</td>
<td>0.6</td>
<td>$0.38^{+0.48}_{-0.11}$</td>
<td>0.48</td>
</tr>
<tr>
<td>$a_{min}$ [$\mu$m]</td>
<td>0.006</td>
<td>$0.009^{+0.003}_{-0.008}$</td>
<td>0.003</td>
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<tr>
<td>$a_{max}$ [$\mu$m]</td>
<td>1.87</td>
<td>$19000^{+31000}_{-9400}$</td>
<td>20200</td>
</tr>
<tr>
<td>$d$ [Å]</td>
<td>3.4</td>
<td>$3.71^{+0.11}_{-0.19}$</td>
<td>3.58</td>
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<tr>
<td>$i[\degree]$</td>
<td>83.6</td>
<td>$83.4^{+2.2}_{-3.0}$</td>
<td>85.1</td>
</tr>
</tbody>
</table>

but

Combination with SED (and constraints from scattered light images) show that inner region is not entirely cleared

[Madlener, Wolf, et al., subm.]
GM Aurigae

**Goal**
Direct imaging of the inner disk rim of transitional disks

**Technique**
VISIR (N band) imaging

**Targets**
GM Aur, DH Tau, DM Tau

**Observed** flux residuals of GM Aur

GM Aurigae

Results

- Transitional disk around GM Aur spatially resolved
- Inner disk radius: 20.5(+1.0,-0.5) AU

- Disks around DH Tau and DM Tau not spatially resolved (consistent with literature values)
  - DH Tau <15.5 (+9.0,-2.0) AU
  - DM Tau <15.5 (+0.5,-0.5)

[Gräfe, Wolf, et al., 2011]
Inner disks – Open questions

Hypotheses / Theoretical model to be tested
- Accretion: Viscosity, Angular momentum transfer, Accretion geometry on star(s)
- Snow-line (location / surface density profile)
- Planets: Luminosity, induced gaps
- Puffed-up inner rim and associated shadowed region
- Gas within the inner rim
- Gas-to-dust mass ratio; Empty(?) holes in transition disks

The general context (exemplary questions):
- How do inner and outer disk relate to each other?
- Where and when do planets form?

Required
Empirically-based input to improve our general understanding and thus to better constrain planet formation / disk evolution models

Approach
Imaging the inner disk
Mid-IR Spectro-Interferometry

• Goal
  – Spectrally resolved (R=30) N band visibilities for various T Tauri disks
  – MIDI: $\lambda/B \geq 1$AU @ 140pc with $B \leq 130$m

• Results
  – SED (global appearance of the disk) + spectrally resolved visibilities can be fitted simultaneously
  – Best-fit achieved in most cases with an active accretion disk and/or envelope
  – Decompositional analysis of the 10μm feature confirms effect of Silicate Annealing in the inner disk (≈ few AU)

• References
Limitation of two-beam interferometers

• **Goal:**
  True surface brightness profile of circumstellar disks

• **Problem**
  – Two-telescope interferometers: “Mean” disk size & approximate disk inclination
  – Assumption: Iso-brightness contours are centered on the location of the central star

• **Solution**
  – **MATISSE**: Multi-AperTure Mid-Infrared SpectroScopic Experiment
  – Second generation VLTI beam combiner
  – L, M, N bands: ~ 3 – 13 mm
  – Spectral resolution: 30 / 100-300 / 500-1000
  – Simultaneous observations in 2 spectral bands

Simulated 10μm intensity map of the inner 30AU×30AU region of a circumstellar T Tauri disk at an assumed distance of 140 pc; inclination: 60°.
MATISSE / Circumstellar disks

Configuration: 7 Nights x 3 ATs
Baselines: B5-J6-J1, B5-D0-J3, B5-B1-D1, B5-M0-G2, J6-A0-J2, J1-D1-G2, J6-A0-M0
Number of Visibilities: 210, Number of Closure Phase Relations: 70

Figure 22: Image reconstruction experiments. Top: uv-coverage of the two reconstruction experiments; Bottom left: original image (see Fig. 21, right) convolved with a PSF corresponding to a 202 m aperture; Bottom center and right: images reconstructed from two data sets with 2% and 5% noise of the squared visibilities (4% and 10% for the simulated closure phases). The reconstruction errors are 0.00020 (2% noise) and 0.00023 (5% noise) using the distance measure $d$ by Lawson et al. (2004).

10μm image of a circumstellar disk with an inner hole; radius 4AU (inclination: 60°; distance 140pc; inner 60AU x 60AU)
Figure 6: Reconstructed $N$ band images (3x4 ATs; $\sim$ 150 m) of a protoplanetary disk with an embedded planet (see Fig. 5(right)). Left: Brighter planet: intensity ratio star/planet=100/1; Right: Fainter planet: intensity ratio star/planet=200/1. First row: uv coverages Second and third row: originals and reconstructions, respectively. The images are not convolved (2x super resolution). Simulation parameter: modelled YSO with planet (declination $-30^\circ$; observing wavelength 9.5 $\mu$m; FOV = 104 mas; 1000 simulated interferograms per snap shot with photon and 10 $\mu$m sky background noise (average SNR of visibilities: 20). See Doc. No. VLT-TRE-MAT-15860-5001 for details.
Exemplary studies

b) Debris disks
Problems with SEDs

[Kim et al. 2005]

Weakly constrained dust properties
HD 107146

Observations

- G2 V, 28.5pc
- Spatially resolved maps
  - HST/ACS (F606W)
  - HST/NICMOS (F110W,F814W)
  - CARMA (1.3mm)
- SED
  - 3.5μm - 3.1mm
  - in particular: Spitzer / IRS (7.6μm - 37μm)

Modeling

- Approach:
  Simultaneous fitting of images and SED
- Fitting tool: SAnD
  - Simulated annealing minimization scheme
  - Fast: finds fit among $\sim 10^{11}$ models in $\sim 70$ hours
  - Large number of free parameters possible
  - Limited initial constraints on disk physics

[ Ertel, Wolf, et al. 2011 ]
HD 107146

- Broad disk, not a narrow ring
  (surface density: FWHM = 91 AU,
   peak radius = 131 AU)

- Radial density distribution: No simple power-law
HD 107146

- Consistent mass estimate from scattered light data and millimeter measurements \((6.4+/-0.3 \times 10^{-7} \, M_{\text{Sun}})\)

- Large lower grain size \((5 \times \text{expected blow-out size})\), robust against uncertainties in model parameters

HST/ACS

[ Ertel, Wolf, et al. 2011 ]
HD 107146

Contours start at $-1\sigma$ (white, dashed) and $1\sigma$ (black, solid) and have increments of $1\sigma$, respectively, where $1\sigma = 0.35$ mJy/beam

Model subtraction: In u-v domain

Two peaks: Artefacts of image reconstruction
Porous grains: Blow-out size

Porous grains in the Solar system

- $T = 5777K$, Astrosilicate
- $a_{\text{min}} = 0.45 \mu m$

[Kirchschlager & Wolf, in prep.]
Porous grains: Blow-out size

Porous grains in the Solar system

- \( T = 5777 \text{K} \),
  Astrosilicate

- \( a_{\text{min}} = 0.45 \mu\text{m} \)

But for

- Hole size
  \( H = 1/100 \)
- \( a_{\text{min}} = 0.74 \mu\text{m} \)
  for \( P=0.5 \)

[Kirchschlager & Wolf, in prep.]
q1 Eri

- **Stellar parameters**
  - Spectral type: F8
  - Distance: 17.4 pc
  - Age: ~2 Gyr

- **Planet**
  (Mayor et al. 2003, Butler et al. 2006)
  - $M\sin i$: 0.93 $M_{Jupiter}$
  - Semi-major axis: 2.03 AU
  - Eccentricity: 0.1

- **Dust ring**
  - IRAS, ISO and Spitzer: cold dust; $L \sim 1000 L$(Kuiper Belt)
  - Sub-mm APEX/LABOCA images:
    Disk extent up to several tens of arcsec (Liseau et al. 2008)
  - HST images suggest a peak at 83 AU (4.8", Stapelfeldt et al., in prep.)
q1 Eri

• Herschel observations (Key project DUNES):

  – Disk spatially resolved at all PACS wavelengths
  – Disk marginally resolved along the minor axis: inclination > 55°

• Detailed simultaneous modeling of the SED and PACS images required to unveil the disk structure, dust properties and dynamical history
q1 Eri

No initial constraints on outer disk radius

Best fit ($\chi_r^2 = 1.24$):

- **Dust disk**:
  - Mass: 0.05 $M_{\text{Earth}}$
  - Surface density: $r^{+0.9}$
  - Disk extent: 17-210 AU

- **Grain properties**:
  - 50-50 silicate-ice mixture
  - Minimum grain size $\sim$ 0.7 $\mu$m
  - Size distribution: -3.3 power law index
q1 Eri

Constraint:
Fixed outer disk radius to large value (600AU)

Best fit ($\chi_r^2 = 1.4$):

- **Dust disk**:
  - Mass: 0.055 MEarth
  - Surface density: $r^{-2}$
  - Belt peak position: 75-80 AU

- **Grain properties**:
  - 50-50 silicate-ice mixture
  - Minimum grain size $\sim 0.4 \mu$m
  - Size distribution: -3.3 power law index
Tracing proto-planets
Tracing gaps with ALMA

Jupiter in a 0.05 $M_{\text{sun}}$ disk around a solar-mass star as seen with ALMA

d=140pc
Baseline: 10km
$\lambda=700\mu$m, $t_{\text{int}}=4$h
Local environment of proto-planets

Procedure

Density Structure ↓
Stellar heating ↓
Planetary heating ↓
Prediction of Observation

[D'Angelo et al. 2002]
[Wolf & D'Angelo 2005]
Tracing proto-planets with ALMA

- $M_{\text{planet}} / M_{\text{star}} = 1M_{\text{Jup}} / 0.5 M_{\text{sun}}$

- Orbital radius: 5 AU

- Disk mass as in the circumstellar disk around the Butterfly Star in Taurus

- Observing conditions
  - Maximum baseline: 10km
  - 900GHz
  - Integration time = 8h
  - Random pointing error during the observation: (max. 0.6")
  - Amplitude error, “Anomalous” refraction
  - Continuous observations centered on the meridian transit
  - Zenith (opacity: 0.15); 30° phase noise
  - Bandwidth: 8 GHz

[ Wolf & D'Angelo 2005 ]
Shocks & MRI

- Strong spiral shocks near the planet are able to decouple the larger particles (>0.1mm) from the gas

- Formation of an annular gap in the dust, even if there is no gap in the gas density.

- MHD simulations - gaps are shallower and asymmetrically wider; rate of gap formation is slowed

Observations of gaps will allow to constrain the physical conditions in circumstellar disks
Multi-wavelength search for disk structures

K band scattered light image (Jupiter/Sun + Disk)
[Disk radius: 20AU]  
[Wolf, 2008]
Multi-wavelength search for disk structures

**AB Aurigae**

**Spiral arm structure: H band**
(Herbig Ae star; SUBARU)
Distance: ~140 pc

K band scattered light image (Jupiter/Sun + Disk)
[Disk radius: 20AU]

[Wolf, 2008]

[Wukagawa et al. 2004]
Multi-wavelength search for disk structures

AB Aurigae
Asymmetry (Color: 24.5μm, Contours: H Band)
(Herbig Ae star; SUBARU)
Distance: ~140 pc

K band scattered light image (Jupiter/Sun + Disk)
[Disk radius: 20AU]

[Wolf, 2008]

[Fujiwara et al. 2006]
Multi-wavelength search for disk structures

AB Aurigae
Spiral (345 GHz, continuum)
(Herbig Ae star; SMA)
Distance: ~140 pc

K band scattered light image (Jupiter/Sun + Disk)
[Disk radius: 20AU]

[Wolf, 2008]

[Lin et al. 2006]
Gaps: The importance of multi-$\lambda$ observations

N band

Gaps as indicators for dust sedimentation height

[Sauter & Wolf 2011]
Tracing planets in debris disks: Imaging required

[ Moro-Martin, Wolf, & Malhotra 2005 ]
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*First guess*
Planets of different mass at similar orbit

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Tracing planets in debris disks: Imaging required

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Solution
Planets of same mass at different orbits

Important: Influence of optical dust properties

[ Moro-Martin, Wolf, & Malhotra 2005 ]
What comes next?

- **Multi-wavelength / Multi-scale intensity measurements**
  - Inner (<10AU) disk structure: Test of disk / planet formation evolution models
  - Distribution of gas species

- **Polarimetry**
  - High-contrast observing techniques
  - Break degeneracies, Magnetic field measurement

- **Near-future goal: Planet-disk interaction**
  - Usually much larger in size than the planet
  - Specific structure depends on the evolutionary stage of the disk
  - High-resolution imaging performed with observational facilities which are already available or will become available in the near future will allow to trace these signatures.
What comes next?

• Self-consistent modeling of dust / gas density & temperature distribution

• Dust properties = f(r,z)

• Additional, independent observables
  Examples:
  – Polarization: High-angular resolution
  – ALMA: High-angular resolution maps
  – ALMA: Submm-wavelengths
  – ALMA: Gas
And hopefully soon ...

Thank you.