Planet Gaps in the Dust Layer of 3D Protoplanetary Disks: Observability with ALMA

Jean-François Gonzalez
Centre de Recherche Astrophysique de Lyon, France

Sarah Maddison
Swinburne University of Technology, Melbourne, Australia

Christophe Pinte, François Ménard
Institut de Planétologie et d’Astrophysique de Grenoble, France

Laure Fouchet
Universität Bern, Switzerland
Motivation

• Protoplanetary disks: science driver for ALMA

• First investigations
  • Hydrodynamical simulations of 2D gas-only disks
  • Synthetic images: 3D structure (gaussian in \( z \)), uniform dust
  • ALMA at its limits (shortest \( \lambda \), longest baselines)
  • Constant 30° phase noise

• Subsequent improvements
  • Simulations of 3D gas+dust disks, self-consistant dynamics
    Barrière-Fouchet et al. (2005), Fouchet et al. (2007)
  • Synthetic images based on resulting 3D dust distribution
    Pinte et al. (2007)
  • More realistic phase noise (GILDAS, CASA)

Wolf et al. (2002), Wolf & D’Angelo (2005)

Pinte et al. (2007)
Hydrodynamical Simulations

- SPH 3D two-phase (gas+dust) code

- CTTS disk
  - $M_{\star} = 1 \, M_{\odot}$
  - $M_{\text{disk}} = 0.02 \, M_{\odot}$

- Initial dust/gas ratio
  - $10^{-2}$

- Grain sizes
  - 100 $\mu$m, 1 mm, 1 cm

- Planet
  - $M_{\text{P}} = 1$ and 5 $M_{\text{J}}$
  - $a = 40$ UA

*Fouchet et al. (2010)*
Raw synthetic images

- 3D SPH particle distribution $\Rightarrow$ 3D density structure on MCFOST grid
- Interpolation as a function of grain size: $dn(a) \propto a^{-3.5} \, da$
- 3D radiative transfer: Monte Carlo + ray tracing
  $\Rightarrow$ Thermal emission maps

MCFOST
Pinte et al. (2006)
Raw synthetic images

\[ \lambda = 350 \, \mu m \quad \lambda = 850 \, \mu m \quad \lambda = 1.3 \, \text{mm} \]

\[ M_P = 1 \, M_J \quad M_P = 5 \, M_J \]
ALMA simulated images

- Instrument simulator for ALMA: synthetic visibilities + thermal noise + phase noise
- Various integration times, \( \lambda \), angular resolutions, distances...
- Reference disk
  - \( i = 18.2^\circ, d = 140 \text{ pc}, \delta = -23^\circ \)
  - median sky quality (pwv = 1.08 mm), no phase noise
ALMA simulated images

$M_P = 1 \, M_J \quad \lambda = 850 \, \mu m$

$\theta = 0.05''$

$\theta = 0.10''$

$\theta = 0.15''$

$\theta = 0.30''$

$\theta = 0.50''$

Flux (mJy/beam)

$t = 10 \, \text{min} \quad t = 30 \, \text{min} \quad t = 1 \, \text{h} \quad t = 2 \, \text{h} \quad t = 4 \, \text{h} \quad t = 8 \, \text{h}$

arcseconds
ALMA simulated images

\( M_P = 1 \ M_j \quad \lambda = 850 \ \mu m \)

\( \theta = 0.05'' \)

\( \theta = 0.10'' \)

\( \theta = 0.15'' \)

\( \theta = 0.30'' \)

\( \theta = 0.50'' \)

\( t = 10 \text{ min} \quad t = 30 \text{ min} \quad t = 1 \text{ h} \quad t = 2 \text{ h} \quad t = 4 \text{ h} \quad t = 8 \text{ h} \)
Optimal parameters

\[ t = 1 \text{ h} \quad \theta = 0.10'' \]

- \( \lambda = 350 \text{ µm} \)
- \( \lambda = 850 \text{ µm} \)
- \( \lambda = 1.3 \text{ mm} \)

\( M_p = 1 \ M_j \quad \ M_p = 5 \ M_j \)
\[ \lambda = 350 \, \mu m \]
\[ \lambda = 850 \, \mu m \]
\[ \lambda = 1.3 \, mm \]

Well-mixed approximation

\[ t = 1 \, h \quad \theta = 0.10'' \]

Dust assumed to follow the gas distribution
Effect of phase noise

\[ t = 1 \text{ h} \quad \theta = 0.10'' \]

Median sky quality
\[ \text{pwv} = 1.08 \text{ mm} \]

Flux (mJy/beam)
Effect of phase noise

$t = 1 \text{ h}$ \hspace{1cm} $\theta = 0.10''$

Median sky quality

\begin{align*}
\lambda &= 350 \mu m \\
\lambda &= 850 \mu m \\
\lambda &= 1.3 \text{ mm} \\
M_P &= 1 \, M_J \\
M_P &= 5 \, M_J
\end{align*}

pwv = 1.08 mm

Best 10% of sky quality

\begin{align*}
M_P &= 1 \, M_J \\
M_P &= 5 \, M_J
\end{align*}

pwv = 0.3 mm

Dry weather
Varying disk inclination

$M_P = 1 \, M_J \quad \lambda = 850 \, \mu m \quad t = 1 \, h \quad \theta = 0.10''$

$i = 18.2^\circ \quad i = 31.8^\circ \quad i = 41.4^\circ \quad i = 49.5^\circ$

$i = 56.6^\circ \quad i = 63.3^\circ \quad i = 69.5^\circ$

$i = 75.5^\circ \quad i = 81.4^\circ \quad i = 87.1^\circ$
Varying distance and declination

$M_p = 1 \, M_J \quad \lambda = 850 \, \mu m \quad t = 1 \, h$

Reference disk @ 140 pc
$\delta = -23^\circ$
$\theta = 0.10''$

Ophiuchus
$\delta = -24^\circ$
$\theta = 0.12''$

Taurus
$\delta = +25^\circ$
$\theta = 0.10''$

Lupus (I)
$\delta = -34^\circ$
$\theta = 0.09''$

Chamaeleon (I)
$\delta = -77^\circ$
$\theta = 0.09''$

Serpens
$\delta = +01^\circ$
$\theta = 0.05''$

Distance

120 pc 140 pc 150 pc 160 pc 260 pc
Pushing ALMA further

\[ t = 8 \text{ h} \quad \theta = 0.05'' \]

Median sky quality

\[ \text{pwv} = 1.08 \text{ mm} \]

Flux (mJy/beam)

\[ \lambda = 350 \mu m \]

\[ \lambda = 850 \mu m \]

\[ \lambda = 1.3 \text{ mm} \]

\[ M_P = 1 \, M_J \quad M_P = 5 \, M_J \]
Pushing ALMA further

\[ t = 8 \text{ h} \quad \theta = 0.05'' \]

Median sky quality

\[ \text{pwv} = 1.08 \text{ mm} \]

\[ \lambda = 350 \mu\text{m} \]
\[ \lambda = 850 \mu\text{m} \]
\[ \lambda = 1.3 \text{ mm} \]

\[ M_P = 1 \, M_J \quad M_P = 5 \, M_J \]

Best 10% of sky quality

\[ \text{pwv} = 0.3 \text{ mm} \]

Dry weather

[Imagery of molecular clouds and gas]
Conclusion

- Pipeline for a systematic study of disks as observed by ALMA
  - 2-phase 3D SPH → radiative transfer → ALMA simulator
- Self-consistent dust dynamics essential for realistic maps
- Gap detection
  - single 1-hour exposure at well chosen $\lambda$ sufficient
- Characterization
  - multi-$\lambda$, longer $t$, smaller $\theta$...
  - distinction from transition disk requires short $\lambda$
- Detectability is robust wrt disk inclination or declination
  ➞ ALMA should routinely observe planet signatures in nearby star-forming regions
More information: