Molecular Diagnostics of Protoplanetary Disk Gaps

Dmitry Semenov, Richard Teague, Uma Gorti
Direct look into planet formation

HL Tau

ALMA: 0.87–3 mm

ALMA Partnership (2015)

Carrasco-Gonzalez et al. (2016)
Direct look into planet formation

HL Tau

ALMA: 0.87–3 mm
ALMA Partnership (2015)

TW Hya

SPHERE: 0.63–1.62 μm
van Boekel et al. (2016), subm.

Carrasco-Gonzalez et al. (2016)
Andrews et al. (2016)
Direct look into planet formation

**HL Tau**
- ALMA: 0.87–3 mm
- ALMA Partnership (2015)

**TW Hya**
- SPHERE: 0.63–1.62 μm
- van Boekel et al. (2016), subm.

**MWC 758**
- SPHERE: 1.04 μm
- Benisty et al. (2015)

**IM Lup**
- DCO⁺ 3–2
- Öberg et al. (2015)

TW Hya disk: dust gaps

Debes et al. (2013)

Akiyama et al. (2015), Rapson et al. (2015), Nomura et al. (2016), Zhang et al. (2016)
TW Hya disk: dust gaps

- NIR μm-dust gap: ~80 au (depth ~50%)

Akiyama et al. (2015), Rapson et al. (2015), Nomura et al. (2016), Zhang et al. (2016)
TW Hya disk: dust gaps

Hubble

Debes et al. (2013)

SPHERE@VLT

van Boekel et al. (2016), subm.

• NIR $\mu$m-dust gap: $\sim$80 au (depth $\sim$50%)

Akiyama et al. (2015), Rapson et al. (2015), Nomura et al. (2016), Zhang et al. (2016)
TW Hya disk: dust gaps

- NIR μm-dust gap: ~80 au (depth ~50%)

Debes et al. (2013)

van Boekel et al. (2016), subm.

Akiyama et al. (2015), Rapson et al. (2015), Nomura et al. (2016), Zhang et al. (2016)
TW Hya disk: dust gaps

• NIR μm-dust gap: ~80 au (depth ~50%)

• Other gaps: <6 and 21 au

Akiyama et al. (2015), Rapson et al. (2015), Nomura et al. (2016), Zhang et al. (2016)
TW Hya disk: dust gaps

- NIR μm-dust gap: ~80 au (depth ~50%)
- Other gaps: <6 and 21 au

Akiyama et al. (2015), Rapson et al. (2015), Nomura et al. (2016), Zhang et al. (2016)
TW Hya disk: dust gaps

- NIR $\mu$m-dust gap:~80 au (depth ~50%)
- Other gaps:<6 and 21 au

Akiyama et al. (2015), Rapson et al. (2015), Nomura et al. (2016), Zhang et al. (2016)
TW Hya disk: dust gaps

- NIR μm-dust gap: ~80 au (depth ~50%)
- Other gaps: <6 and 21 au
- ALMA mm-dust gaps: 1, 22, 25, 37, ~43 au

Akiyama et al. (2015), Rapson et al. (2015), Nomura et al. (2016), Zhang et al. (2016)
TW Hya disk: gap at 80 au

SPHERE, 1.62μm

van Boekel et al. (2016), subm.

ALMA, CS (5–4) x r^2

Teague et al. (2016), in prep.
TW Hya disk: gap at 80 au

SPHERE, 1.62 μm

van Boekel et al. (2016), subm.

ALMA, CS (5–4) x r²

Teague et al. (2016), in prep.
TW Hya disk: gap at 80 au

- CS gap @ 80 au, width ~20 au

van Boekel et al. (2016), subm.

Teague et al. (2016), in prep.
TW Hya disk: gap at 80 au

- CS gap @ 80 au, width ~20 au
- Gas or dust change?

van Boekel et al. (2016), subm.

Teague et al. (2016), in prep.
TW Hya disk: gap at 80 au

- CS gap @ 80 au, width ~20 au
- Gas or dust change?
- Excitation or chemistry?

van Boekel et al. (2016), subm.
Teague et al. (2016), in prep.

ALMA, CS (5–4) x r²

SPHERE, 1.62 μm

ALMA C2: 2013.1.00387.S
TW Hya disk modeling

- Thermochemical disk model
TW Hya disk modeling

- Thermochemical disk model

Brinch & Hogerheijde (2010), Semenov et al. (2010), Gorti et al. (2011)
TW Hya disk modeling

- Thermochemical disk model
- Gas-grain chemistry (ALCHEMIC)

Brinch & Hogerheijde (2010), Semenov et al. (2010), Gorti et al. (2011)
TW Hya disk modeling

- Thermochemical disk model
- Gas-grain chemistry (ALCHEMIC)
- Non-LTE line radiative transfer (LIME)

Brinch & Hogerheijde (2010), Semenov et al. (2010), Gorti et al. (2011)
TW Hya disk modeling

- Thermochemical disk model
- Gas-grain chemistry (ALCHEMIC)
- Non-LTE line radiative transfer (LIME)

CASAALMA simulations

\[
\log_{10} n(H) \text{ (cm}^{-3}) \quad \log_{10}(n_H, \text{cm}^{-3})
\]

\[
T_{\text{gas}} \text{ (K)} \quad T_{\text{gas, K}} \quad T_{\text{dust}} \text{ (K)} \quad T_{\text{dust, K}}
\]

Brinch & Hogerheijde (2010), Semenov et a. (2010), Gorti et al. (2011)
Disk models with 80-au gap

- Gaussian gap: \( \nu(r) = \nu_0(r) \rightarrow \sqrt{1 - d \cdot \exp \left( - \frac{1}{2} \frac{(r - d_0)^2}{f_{j,d}} \right) } \)
Disk models with 80-au gap

- Gaussian gap: $\hat{\nabla}(r) = \hat{\nabla}_0(r) \rightarrow \sqrt{1 - d \cdot \exp \left( -\frac{1}{2} \frac{(r - d_0)^2}{f_j d^2} \right)}$

- Shallow gap: $\Delta d = 20\text{ au}, d = 30\%$ (Debes et al. 13)
Disk models with 80-au gap

• Gaussian gap: \( \eta(r) = \eta_0(r) \rightarrow \sqrt{1 - d \cdot \exp \left( -\frac{1}{2} \frac{(r - d_0)^2}{f_j d^2} \right)} \)

• Shallow gap: \( \Delta d = 20 \text{ au}, d = 30\% \) (Debes et al. 13)

• Deep gap: \( \Delta d \approx 10 \text{ au}, d = 100\% \)
Disk models with 80- au gap

- Gaussian gap: $\mathcal{G}(r) = \mathcal{G}_0(r) \rightarrow \sqrt{1 - d \cdot \exp \left(-\frac{1}{2}\frac{(r - d_0)^2}{f j, a^2}\right)}$

- Shallow gap: $\Delta d = 20$ au, $d = 30\%$ (Debes et al. 13)

- Deep gap: $\Delta d \approx 10$ au, $d = 100\%$

- Dust vs gas perturbation
Disk models with 80-au gap

• Gaussian gap: \( \Delta (r) = \Delta_0 (r) \rightarrow 1 - d \cdot \exp \left( - \frac{(r - d_0)^2}{2f r d^2} \right) \)

• Shallow gap: \( \Delta d = 20 \text{ au}, d = 30\% \) (Debes et al. 13)

• Deep gap: \( \Delta d \approx 10 \text{ au}, d = 100\% \)

• Dust vs gas perturbation

\[
\begin{align*}
\text{Log}_{10}(n_H, \text{cm}^{-3}) & \quad T_{\text{gas}, \text{K}} & \quad T_{\text{dust}, \text{K}} \\
\text{Height, au} & \quad \text{Radius, au} & \quad \text{Radius, au}
\end{align*}
\]
Impact of gap on chemistry

Model A
Model B
Model C

CS column density, cm$^{-2}$

dust gap

gas gap
Impact of gap on chemistry

- Shallow model is too shallow

![Graph showing impact of dust and gas gaps on CS column density.]

- Dust gap
- Gas gap

CS column density cm$^{-2}$

Model A  Model B  Model C
Impact of gap on chemistry

- Shallow model is too shallow
- Dust density ↓ => freeze-out ↓ => N(CS) ↗
• Shallow model is too shallow

• Dust density $\downarrow$ => freeze-out $\downarrow$ => $N(\text{CS})$ $\uparrow$

• Gas density $\downarrow$ => $N(\text{CS})$ $\downarrow$
Impact of gap on radiative transfer

$I_v$ (mJy km s$^{-1}$ pix$^{-1}$)

dust gap

gas gap

CS (5–4), LIME
Impact of gap on radiative transfer

CS (5–4), LIME

CS (5–4), CASA, beam 0.5"

Deprojected radius, ″

$I_v$ (mJy km s$^{-1}$ pix$^{-1}$)
Impact of gap on radiative transfer

- Integrated flux: 2% agreement with data

CS (5–4), LIME

CS (5–4), CASA, beam 0.5"

Deprojected Radius (°)

Model A
Model B
Model Bd
Model C
Model Cd

Integrated flux: 2% agreement with data
Impact of gap on radiative transfer

- Integrated flux: 2% agreement with data
- CS intensity follows N(CS)
Impact of gap on radiative transfer

• Integrated flux: 2% agreement with data
• CS intensity follows N(CS)
• Gas density gap, depth >50%

CS (5–4), LIME

CS (5–4), CASA, beam 0.5″
Origin of the TW Hya 80-au gap
Origin of the TW Hya 80-au gap

- Purely due to dust evolution
Origin of the TW Hya 80-au gap

- Purely due to dust evolution
Origin of the TW Hya 80-au gap

• Purely due to dust evolution

• Opened by a gas planet: $\sim 0.05 - 0.5 \text{ M}_\text{Jup}$
Origin of the TW Hya 80-au gap

• Purely due to dust evolution

• Opened by a gas planet: \( \sim 0.05–0.5 \text{ M}_{\text{Jup}} \)

• Opened by disk instability: outer edge of \( \sim 60\text{-au} \) „dead“ zone
Origin of the TW Hya 80-au gap

• Purely due to dust evolution

• Opened by a gas planet: $\sim 0.05-0.5 \, M_{\text{Jup}}$

• Opened by disk instability: outer edge of $\sim 60$-au „dead“ zone

• Future diagnostics: continuum + line spectra at $<0.5$"