New ALMA Long Baseline Observations of the Transitional Disk around TW Hya

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Introduction: TW Hya

- Nearest PPD at d~54pc
- Face-on disk (i=7°)
  => Good lab. for investigate radial structure of disk

- Gapped disk has been resolved
  - NIR and Submm.
  - Physical properties may be varied at 20-30 au
    - It possibly associates with CO snow line [Qi+2013]
Previous work (Nomura et al. 2016) & Motivation

- ALMA cycle 2 obs. in 2015
- Potential gap at ~25 au
  - Width and depth are consistent with clearing by super $M_{\text{Nep}}$ planet
- Dust size distribution is key for understand the origin
  - Large grains are filtered out at the gap edge due to dust filtration [Zhu+2012]

**Purposes of this study**
- To confirm the gap with higher resolution
- To reveal the dust size distribution across the gap from spectral index at submillimeter
ALMA Observation (cycle 3 DDT)

- 1 & 2 Dec. 2015
  - Cycle 3 DDT
  - Array Config.: C36-7 to C36-1
- Continuum at band 4 & 6
- Multi frequency synthesis (MFS)
  - Combined intensity map (~190GHz)
  - Spectral index map
  - Resolution: 3.9x2.9 au
- Sparse UV coverage <200kl
  - North-South direction (v-axis)
  - Band 6 archival data was added, not for band 4
    => artifact in the spectral index map
Multiple gaps and rings
Inner hole structure is marginally resolved
=> consistent with band 7 image [Andrews+2016]

Clear gaps at 22 & 37 au
Weak (a few %) declines of intensity at 6, 28, 44 au
Band 4+6 (190GHz) Combined Image

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- Clear gaps at 22 & 37 au
- Weak (a few %) declines of intensity at 6, 28, 44 au
- Radial variation of $\alpha$
- Non-axisymmetric due to sparse UV coverage along $\nu$-axis at band 4
  - E-W direction is reliable
- $\alpha$ decreases 3 -> 2 toward the center
- Enhancement at 22 au gap
Spectral Index Map

- Radial variation of $\alpha$
- Non-axisymmetric due to sparse UV coverage along v-axis at band 4
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Optical Depth $\tau$ and Dust Opacity index $\beta$

- $\tau$ & $\beta$ are derived from $I_{190\text{GHz}}$ and $\alpha$
  \[ I_{\nu}(R) = B_{\nu}(T_d(R)) \left(1 - \exp[-\tau_{\nu}]\right) \]
  \[ \alpha(R) \equiv \frac{d \log(I_{\nu})}{d \log \nu} = 3 - \frac{T_0}{T_d(R)} \frac{e^{T_0/T_d(R)}}{e^{T_0/T_d(R)} - 1} + \beta(R) \frac{\tau_{\nu}(R)}{e^{\tau_{\nu}(R)} - 1}. \]
- $T(R)=T_{10}(R/10\text{au})^{-0.3}$ is assumed and $T_{10}$ is varied 22-30K [Andrews+2012]

- Optically thin $R>15\text{au}$, marginally thick at inner $R$
- $\beta_{\text{peak}} \sim 1.7$ at 22 au gap ($\sim$ISM)
  $\Rightarrow$ large grains deficit inside the gap
  Consistent with the picture of dust filtration by a planet [Zhu+2012]
Gap Structure

- Model fitting using inner hole + 2 prominent gaps
  \[ \tau_{bg} = \tau_0 (R/10 \text{ au})^{-g} \]
  \[ f_{gap} = 1 + (10^{A_g} - 1) \exp \left[ -\frac{(R - r_g)^2}{w_g^2} \right] \]
  \[ \tau_{model}(R) = \tau_{bg}(R) \times f_{gap, in} \times f_{gap, 22 au} \times f_{gap, 37 au} \]
  - Best fits of gap parameters are obtained by least square method for several of \( g \) & \( T_{10} \)

- Parameters of 22 au gap (case of \( T_{10} = 22 \text{K}, g = 1.1 \))
  - \( W_g: 4.7 \pm 0.3 \text{ au} \)
  - \( A_g: -0.39 \pm 0.03 \) (\( \sim 60\% \) of \( \tau_{bg} \))
Expected Planet Mass for Planet-induced Gap

- Width and depth of gap are related to planet mass [Kanagawa et al. 2015, 2016]
- Observed width and depth could be opened by a super-Neptune mass planet
  - Consistent with our cycle 2 results if Width*Depth = const.
- \( \alpha = 10^{-3}, \frac{h}{R} = 0.05 \)

\[
\text{Width \( \Delta_{\text{gap}} \) [AU] at } R_p = 22 \text{AU}
\]

\[
\frac{\text{Depth (} \Sigma_0 - \Sigma \text{)/}\Sigma_0}{\text{Planetary Mass } M_p \text{ [M}_\text{Jup}\text{]}}
\]

#Planet mass is upper limit because Kanagawa’s formula is for gas gap
Summary

• We carried out multi-band ALMA long baseline observations at band 4 and 6
  • Multiple gaps/rings are resolved
  • Radial variation of the spectral index is found
• Optical depth $\tau$ and dust opacity index $\beta$ are derived
  • Disk is thin $R>\sim15$, while the inner part is marginally thick.
  • $\beta$ decreases toward the disk center $\sim1.5$ to 0
  • $\beta$ peaks at 22 au gap
• 22 au gap could be caused by planet-disk interaction
  • Large grain deficit at the gap, consistent with dust filtration
  • Width and depth agree with theoretical prediction of $M_{\text{Nep}}$ planet