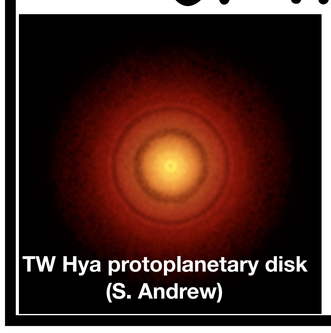
The Synthetic ALMA Multiband Analysis of the dust properties of the TW Hya protoplanetary disks


TW Hya protoplanetary disk (S. Andrew)

Seongjoong Kim[1], Nomura Hideko[1], Takashi Tsukagoshi[2], Ryohei Kawabe[3], Takayuki Muto[4]

[1]Department of Earth and Planetary Sciences, Tokyo Institute of Technoloty, Tokyo 152-0027, Japan

[2]College of Science, Ibaraki University, Bunkyo 2-1-1, Mito, Ibaraki 310-8512, Japan

[3]National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

[4]Division of Liberal Arts, Kogakuin University, 1-24-2 Nishi-Shinjuku, Shinjuku-ku, Tokyo 163-8677, Japan

Abstract

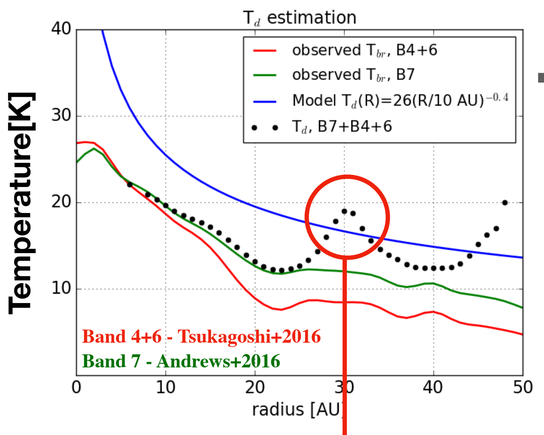
TW Hya is one of the well studied protoplanetary disks (PPDs) with its proximity. Recently, high spatial resolution ALMA observations have revealed clear gap structures and the radial profiles of dust properties of the disk (e.g., Andrews et al. 2016, Tsukagoshi et al. 2016). Multi-band observations of dust continuum emission is useful to constrain the radial profiles of dust temperature and dust opacity which help us to understand physical and chemical properties, such as dust evolution as well as locations of snowlines, in the disk. In this work, we have performed the sensitivity analysis of the synthetic ALMA observations to find the best set of ALMA multi-band observation for constraining dust properties of TW Hya PPD. First, we derived radial profiles of dust temperature T_d, optical depth τ_ν, and opacity power-law index β with the assumption of $\kappa_\nu \propto \nu^\beta$ using the existing ALMA Band 4, 6 and 7 high spatial resolution data. However, this dataset was too sensitive to the errors in observed intensity so that only 10% errors make it difficult to make constraint on T_d, τ_ν, and β. Thus, we have performed Synthetic ALMA Multi-band Analysis in order to find the best ALMA band set. Our result suggests the best set is ALMA Band [10,7,3] and there are two conditions for good constraint on T_d, τ_ν, and β; (1) the combination of one band from Band 9 or 10 and one band from Band 3 or 4 and (2) enough frequency intervals between the selected bands.

1. Motivation

- Estimation of T_d, τ_ν and β from ALMA Band 7, 6, and 4 data with the assumptions,

$$I_\nu(R) = B_\nu(T_d(R))\,(1-exp[-\tau_\nu]) \;,\; \kappa_\nu \propto \nu^\beta$$

$$\alpha(R) = \frac{d\log(I_\nu)}{d\log\nu} = 3 - \frac{h\nu}{k_B T_d(R)} \frac{e^{h\nu/k_B T_d(R)}}{e^{h\nu/k_B T_d(R)}-1} + \beta(R) \frac{\tau_\nu(R)}{e^{\tau_\nu(R)}-1}$$



A large bump around 30 AU by high sensitivity against the observational error

What is **the best set of 3 ALMA bands** giving us a good constraint on T_d, τ_ν and β?

Figure 1. [Top] T_d radial profile estimation by ALMA multi-band data (Band 4+6 and 7). **[Bottom]** The sensitivity map of T_d for ±10% Intensity errors of I_{B4+6} and I_{B7} at 30 AU.

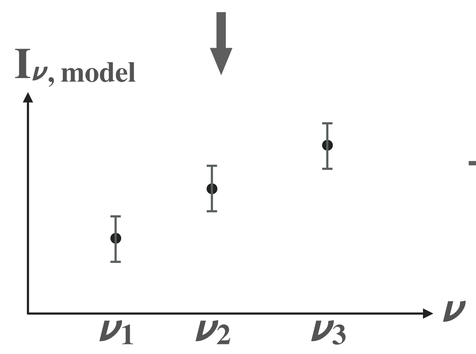
2. The Synthetic ALMA Multiband Analysis

1) Calculation of $I_{\nu,\,model}$

$$I_\nu(R) = B_\nu(T_d(R))\,(1-exp[-\tau_\nu]) \;,\; \kappa_\nu \propto \nu^\beta$$

$T_{d,model}(R) = 26K\,(R/10AU)^{-0.4}$

$\tau_{\nu,model}(R)$ & $\beta_{model}(R)$ from ALMA Band 4&6



2) Sensitivity Analysis

Finding possible range of $T_{d,syn}$, $\tau_{\nu,syn}$, and β_{syn} within ±10% error of $I_{\nu,\,model}$

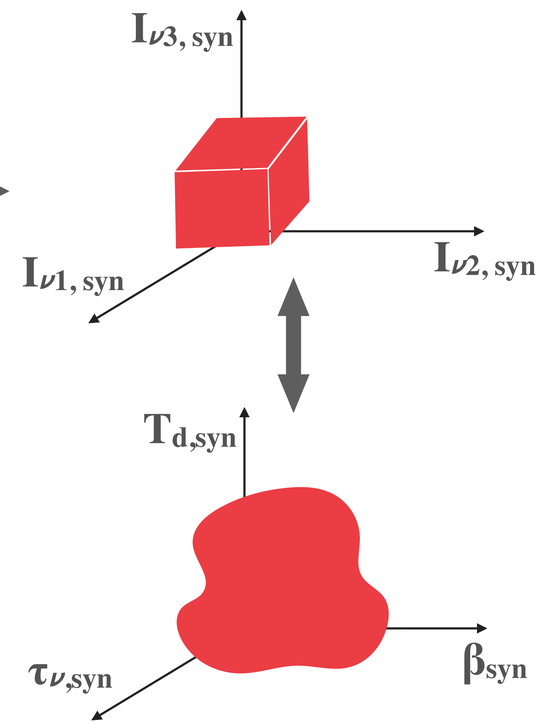


Figure 2. Schematic figure of Synthetic ALMA Multi-band Analysis. The possible range of $T_{d,syn}$, $\tau_{\nu,syn}$, and β_{syn} are translated from the range of ±10% error of $I_{\nu,model}$.

3. Results

- For all possible 3-band combination of ALMA Band [3,4,5,6,7,8,9,10], **the Best result is [10,7,3] combination.**
- **2 conditions for good constraint** on T_d, τ_ν and β
  - (1) One band from **Band 9 or 10** + One band from **Band 3 or 4**
    ex) [10,7,3], [10,8,3], [9,7,3], [9,8,3] ≫ [7,6,4]
  - (2) **Enough frequency intervals** between the selected bands
    ex) [10,7,3] > [10,8,3] > [9,7,3] > [9,8,3]

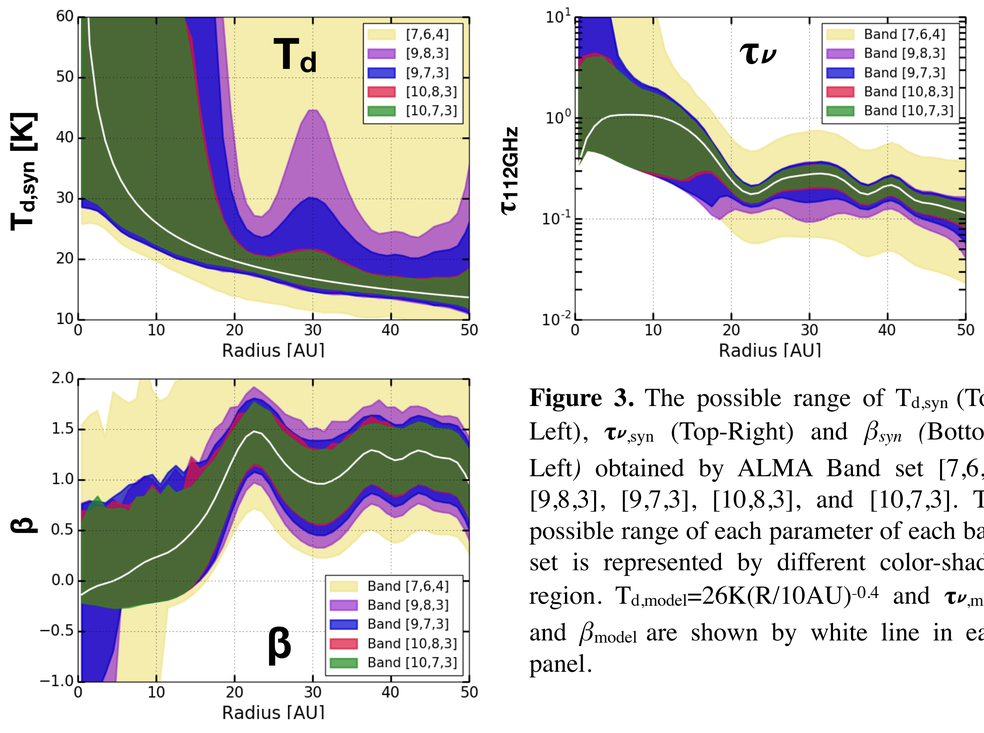


Figure 3. The possible range of $T_{d,syn}$ (Top-Left), $\tau_{\nu,syn}$ (Top-Right) and β_{syn} (Bottom-Left) obtained by ALMA Band set [7,6,4], [9,8,3], [9,7,3], [10,8,3], and [10,7,3]. The possible range of each parameter of each band set is represented by different color-shaded region. $T_{d,model}=26K(R/10AU)^{-0.4}$ and $\tau_{\nu,model}$ and β_{model} are shown by white line in each panel.

4. Discussion

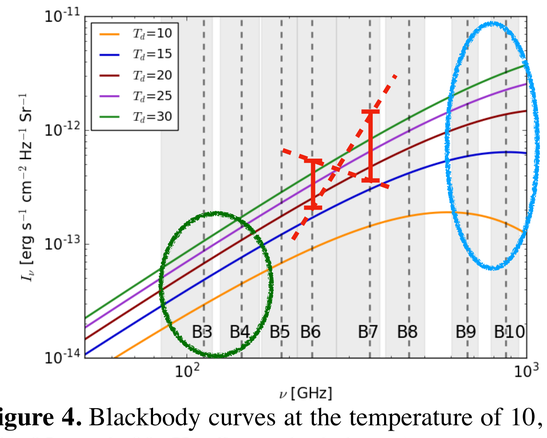


Figure 4. Blackbody curves at the temperature of 10, 15, 20, 25, and 30 K. Gray shaded regions present the coverage of ALMA Band 3 to 10.

- **Reasons of 2 conditions for good constraint on T_d, τ_ν and β**
  - **(1)** **Band 9 & 10:** Deviated from Rayleigh-Jeans limit
    ⇒ more degree of freedom to fit T_d and τ_ν
  - **(2)** **Band 3 & 4**: Optically thin band
    ⇒ Information of τ_ν
  - **(3)** **Enough frequency intervals** between the selected bands
    ⇒ Enough $\Delta\nu$ reduces the error of SED slope fitting caused by the observational error

5. Application to [9,6,4] data

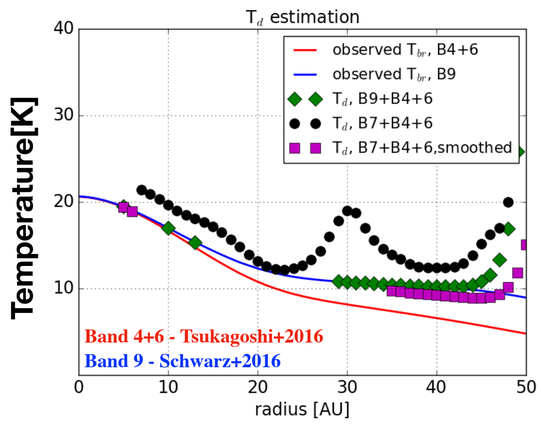


Figure 5. Estimated T_d (Green diamond) using ALMA Band [9,6,4] combination. Compared to Band [7,6,4] (Black point), it has relatively smooth profile around 30 AU. However, smoothed Band [7,6,4] result (Magenta square) indicates it is smoothing effect.

- We apply the same analysis to Band [9,6,4] data confirming the consistency of the Synthetic ALMA Multiband Analysis.
  - ✓ **Band [9,6,4] vs Band [7,6,4]**: **[9,6,4]** doesn't show any bump around 30 AU
    ⇒ It looks consistent with our analysis
  - ✓ **Smoothed Band [7,6,4] vs Band [7,6,4]**: Beam~ **0.4″× 0.2″** vs ~ **0.088″× 0.061″**
    ⇒ The bump around 30 AU is smoothed out by large beam of Band 9

6. Summary

Synthetic ALMA Multiband Analysis to constrain T_d, τ_ν and β accurately.

- **The best set of ALMA bands is [10, 7, 3]**
- **2 conditions for good constraint**
  1. **One band from Band 9 or 10 & One band from Band 3 or 4**
  2. **Enough frequency intervals between selected bands**

❖ Reference

1. Andrews, S. M., Steinfelds, E., Zolman, N. et al.2016, ApJL, 820, L40
2. Tsukagoshi, T., Nomura, H., Muto, T. et al. 2016, ApJL, 829, L35
3. Schwarz. K. R., Bergin, E. A., Cleeves, L. I. et al 2016, ApJ, 823, 91S