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

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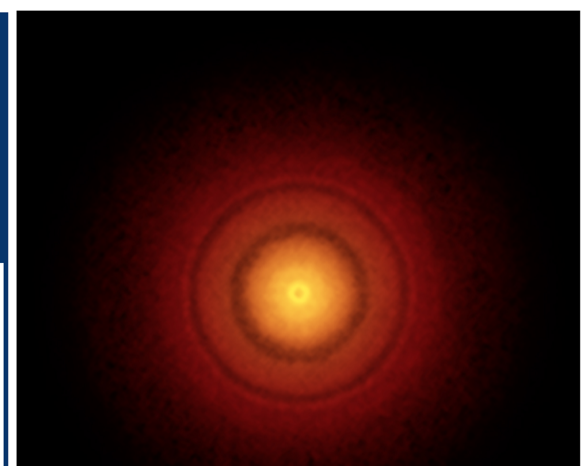
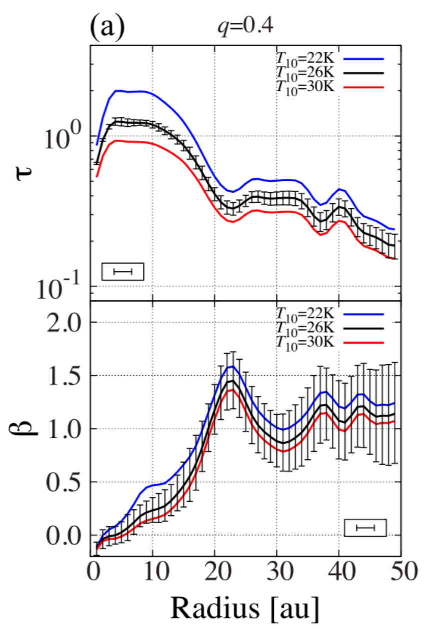


TW Hya protoplanetary disk (S. Andrew)

• Abstract

Recently, high spatial resolution ALMA observations have revealed clear gap structures and the radial profiles of dust properties of the TW Hya disk (e.g., Andrews et al. 2016, Tsukagoshi et al. 2016). Multiband observations of dust continuum emission are useful for constraining the radial profiles of dust temperature and dust opacity which help us to understand physical and chemical properties in the disk. In this work, we perform the synthetic multiband analysis to find the best ALMA band set for constraining the dust properties of the TW Hya disk. We find two conditions for the good ALMA band sets providing narrow constraint ranges on dust properties; 1) Band 9 or 10 is included in the band set and 2) Enough frequency intervals between the bands. These are related with the conditions which give good constraints on dust properties; including both optically thick and thin bands in the band set, large β ($\kappa_\nu \propto \nu^\beta$), and low dust temperature and high-frequency bands. To examine our synthetic multiband analysis results, we apply the multiband analysis to ALMA archival data of the TW Hya disk at Band 4, 6, 7, and 9. Band [9,6,4] set provides the dust properties close to the model profile, while Band [7,6,4] set shows the deviations of dust properties from the model profile with broader constraint range. Based on these features, we conclude that the synthetic multiband analysis is consistent with the results derived from real data. We need high spatial resolution observations at Band 9 or 10 and wider frequency coverage for better constraints on the dust properties.

1. Motivation



- Tsukagoshi et al. 2016 derived τ_{190GHz} and β profile from dust continuum at ALMA Band 4 and 6 with assumed T_d=26K(r/10au)$^{-0.4}$

  ⇒ Dust properties derived from observed data are important to distinguish the models of gap formation in the disks!!

Since T_d is strongly affected by the dust properties, it is important to derive the T_d profile directly from the observations.

⇒We can drop the T_d assumption by adding one more observation at different band!!

2. The synthetic multiband analysis

We perform the synthetic multiband analysis to find the best set of three ALMA bands providing the accurate dust properties

Assumptions:

1. Dust opacity $\kappa_\nu \propto \nu^\beta$
2. Vertically homogeneous disk

Equations:

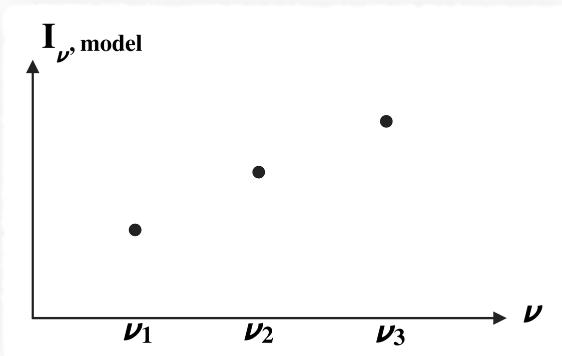
1. $I_\nu(r) = B_\nu(T_d(r))\,(1-\exp(-\tau_\nu(r)))$
2. $\tau_\nu(r) = \tau_0(r)\,(\nu/\nu_0)^{\beta(r)}$
3. $\alpha(r)=3-\frac{h\nu}{k_B T_d(r)}\frac{e^{h\nu/k_B T_d(r)}}{e^{h\nu/k_B T_d(r)}-1}+\beta(r)\frac{\tau_\nu(r)}{e^{\tau_\nu(r)}-1}$

Step 1. Estimate the model Intensities

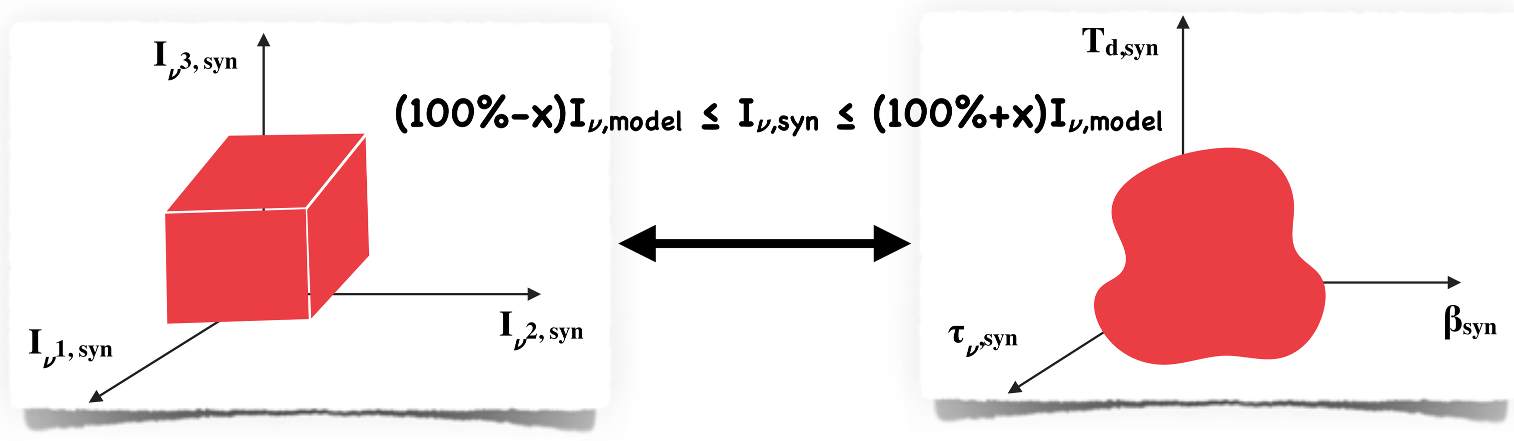
(1) $T_{d,model}(r)$=26K(r/10AU)$^{-0.4}$
(2) $I_{\nu,obs}$ at Band 4 & 6

Pick $[\nu_1,\nu_2,\nu_3]$ among Band [3,4,5,6,7,8,9,10]

$\tau_{0,model}(r)$, $\beta_{model}(r)$

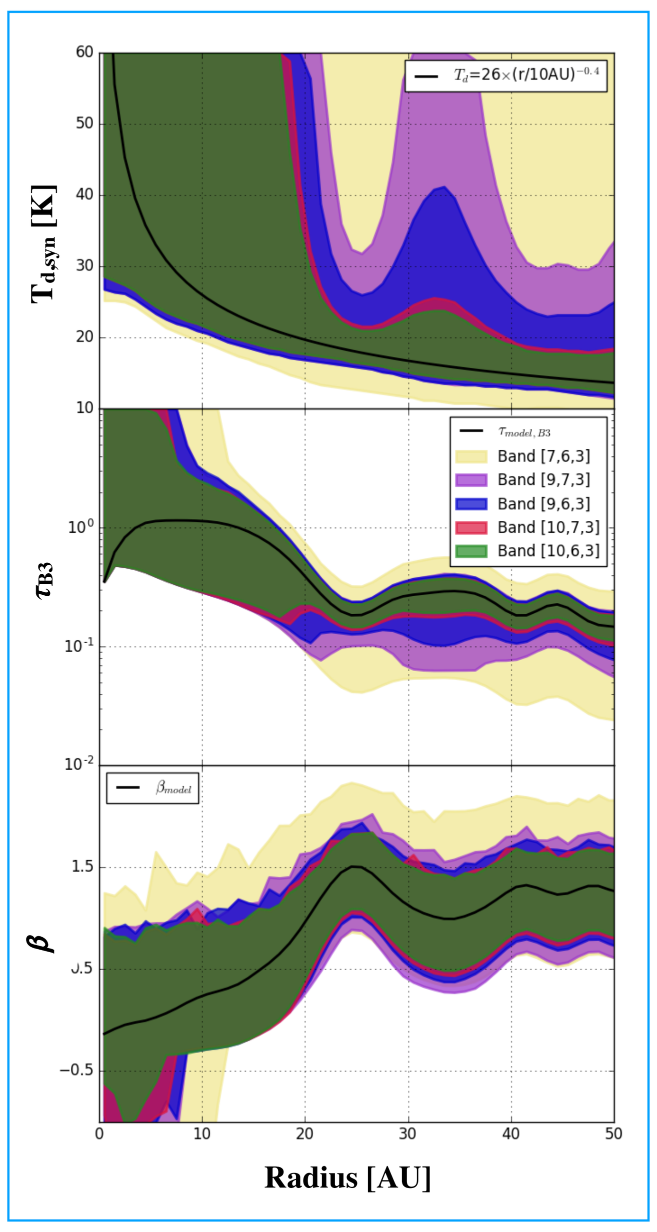


Step 2. extract the synthetic dust properties corresponding to the model intensities and observational errors



where x=10% for Band 3,4,5,6 x=15% for Band 7,8 x=20% for Band 9,10

3. The synthetic multiband analysis results



The derived T_d (top), τ_{B3} (middle), and β (bottom) profiles from different ALMA band sets by the synthetic multiband analysis

- Among 56 combinations, we got some good band sets providing accurate constraints on the dust properties.

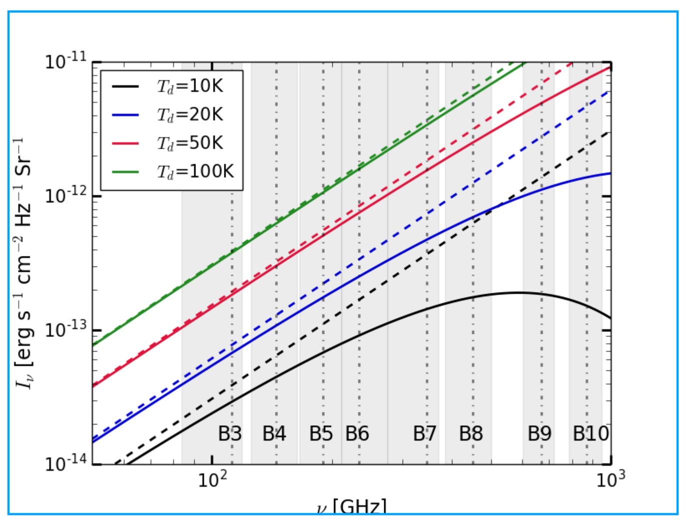
  Ex) [10,6,3] (green), [10,7,3] (red), [9,6,3] (blue), [9,7,3] (purple)

- **Two conditions for good band set**
  1) Band 9 or 10 is included in the set
  2) Enough frequency intervals between the bands

4. Interpretation

- The τ_ν effect
  - i. High τ_ν → $I(r) \simeq B_\nu(T_d(r))$
    - → Good T_d constraints
  - ii. low τ_ν → $I(r) \simeq B_\nu(T_d(r))\tau_\nu$
    - → Good τ_ν constraints
- The β effect: large β
  - → optically thick at high ν band and optically thin at low ν band

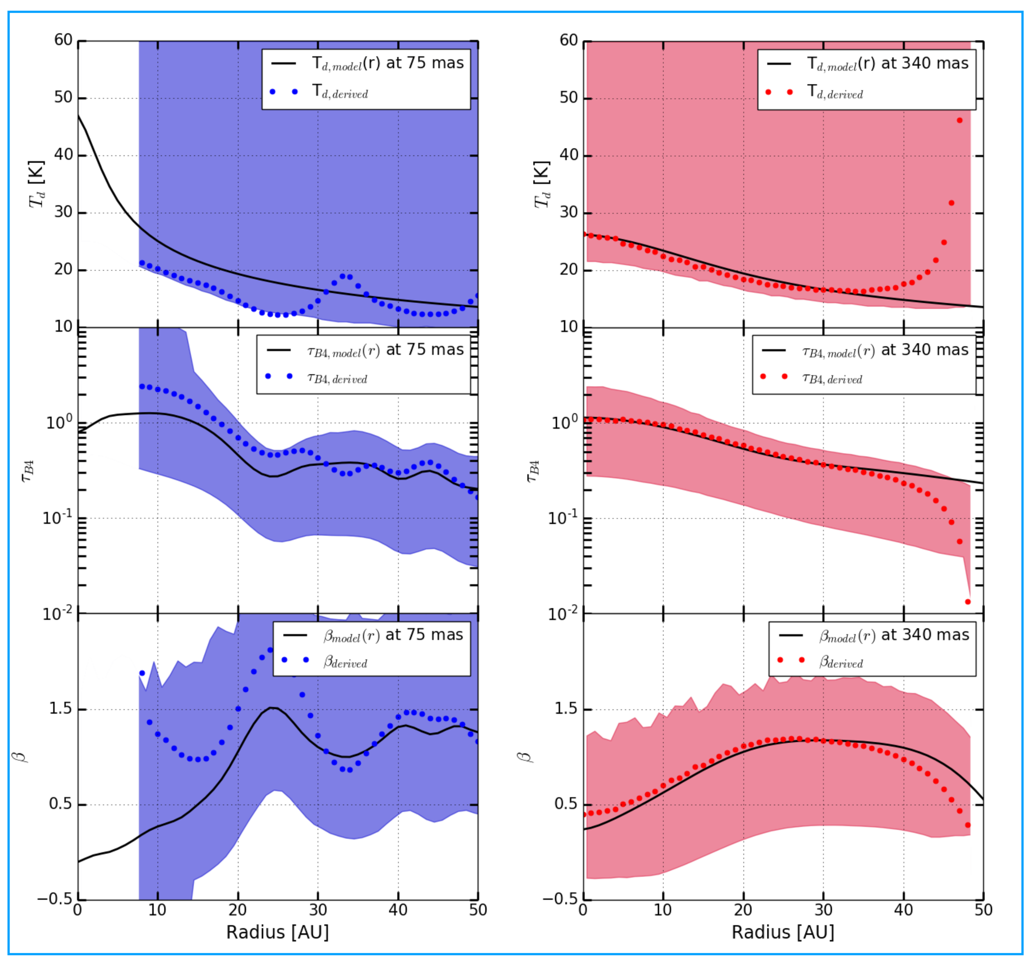
  ⇒ the combination of optically thick and thin bands is needed in order to constrain the dust properties simultaneously
- The T_d effect: Low T_d and high ν bands
  - → Deviation from Rayleigh-Jeans limit ↑
  - → Better constraints on T_d
- The $\triangle\nu$ effect: Enough $\triangle\nu$
  - → better constraint on spectral index α



The blackbody curves at T_d=10, 20, 50, and 100 K. represented by solid line. The dashed lines are Rayleigh-Jeans limit ($I_\nu \propto \nu^2$) at the same T_d

5. Applications to ALMA archival data

Band [7,6,4] set   Band [9,6,4] set



The derived T_d (top), τ_{B4} (middle), and β (bottom) profiles from the Band [7,6,4] and [9,6,4] set by the synthetic multiband analysis

- To examine the consistency of the synthetic analysis result, we apply the multiband analysis to ALMA archival data

(1) Band 4 & 6 (Tsukagoshi+2016): ~0.088″×0.062″
(2) Band 7 (Andrews+2016): ~0.024″×0.018″
(3) Band 9 (Schwarz+2016): ~0.434″×0.251″

⇒ High resolution set ([7,6,4]) & low resolution set ([9,6,4])

- The derived dust properties are
  - deviated from the model profiles for Band [7,6,4] set
  - close to the model profiles for Band [9,6,4] set
- Band [9,6,4] set is better than [7,6,4]

⇒ It is consistent with the synthetic multiband analysis

- The large beam size of Band 9 smoothes out the gap structure in the disk

⇒ We need high resolution observation at Band 9 and wider ν coverage for better constraints on the dust properties

6. Discussion

i) Homogeneous vertical structure of the disk?

We assumed Homogeneous vertical structure of the disk for the calculation. But, there are many evidences that the gradients of T_d along the vertical direction of the disks (e.g. Chiang & Goldreich 1997; Dullemond et al. 2002; Inoue et al. 2009)

ii) The frequency dependence of β?

We assumed a fixed β_ν for the calculations. According to the dust models, however, the dust opacity has the dependence on the frequency and dust temperature. (e.g. Miyake & Nakagawa 1993; Chihara et al. 2002; Draine 2006)

➤ Additional ALMA band data will help us to constrain vertical temperature profile or frequency dependence of β if they exist.

References
• Andrews et al. 2016, ApJL, 820, 40L • Chiang, E. I., & Goldreich, P. 1997, ApJ, 490, 368, • Chihara, H., Koike, C., Tsuchiyama, A., Tachibana, S., & Sakamoto, D. , • Draine, B. T. 2006, ApJ, 636, 1114, • Dullemond, C. P., van Zadelhoff, G. J., & Natta, A. 2002, A&A, 389, 464, • Inoue, A. K., Oka, A., & Nakamoto, T. 2009, MNRAS, 393, 1377 , • Miyake, K., & Nakagawa, Y. 1993, Icarus, 106, 20 • Tsukagoshi et al. 2016, ApJL, 829, 35L • Schwarz et al. 2016, ApJ, 823, 91