The Effect of Dust Scattering on Spectral Indices in Upper Scorpius

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Abstract

We study the properties of dust in protoplanetary disks to constrain models of planet formation using observations from the Atacama Large Millimeter/submillimeter Array (ALMA) at millimeter wavelengths We are analyzing the dust continuum emission in protoplanetary disks around 24 young stars (5-10 My) in the Upper Scorpius star forming region to extract spectral indices and investigate the role of grain growth and dust self-scattering. In the optically thin regime, the spectral index is related to the dust opacity index β, and hence to grain size, allowing us to probe grain growth in these disks. We incorporate updated stellar properties using improved measurements from the Gaia space telescope and combine these with radiative transfer modeling to test whether self scattering can explain the low spectral indices observed in a subset of disks in our sample.

Introduction

- ALMA disk dust masses often fall short of what's needed to build known exoplanet systems (the mass budget problem) [2];
- If disks are optically thick rather than thin as assumed, standard ALMA estimates would underestimate the true dust mass [3];
- Spectral index α ($F_\nu \propto \nu^\alpha$) is the diagnostic, where the Rayleigh-Jeans limit for optically thick emission predicts $\alpha \approx 2$;
- Yet ALMA has resolved several disks (TW Hya, HD 163296) with $\alpha < 2$ in their inner regions [4];
- Self-scattering in optically thick disks with frequency-increasing albedo reproduces $\alpha < 2$, for grain sizes of ~10–100 μm [4] up to ~0.1–1 mm [3];
- This work tests whether the same self-scattering bias extends to Upper Sco's older (5-10 Myr) disks, lowering α_{obs} and underestimating dust masses for disks near the end of their planet-forming window.

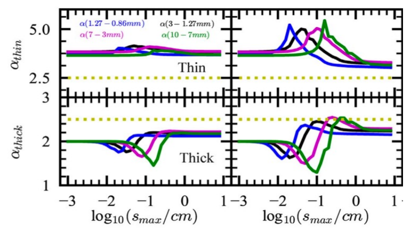

Figure 1: α_{thin} and α_{thick} vs s_{max} for q = -3.5, -4.2 where s_{max} = maximum grain size. Only α_{thick} drops below 2 for $s_{max} \approx 0.01 - 0.1\ cm$ (Zhu et al. 2019).

Methodology

Data Set

- Sample of 24 Class II Upper Scorpius disks, selected as the brightest sources (a flux-limited subsample) in the 106-object 0.88mm ALMA survey [1];
- Flux densities for unresolved sources extracted from 2.87mm ALMA data via CASA aperture photometry [5];
- Stellar distances and luminosities updated using Gaia DR3 parallaxes; stellar masses derived by interpolating T_{eff} onto magnetic PMS evolutionary tracks [6];

Spectral index

- α_{obs} from flux-frequency slope at 0.88mm and 2.87mm;
- α_{Planck} from the Planck function slope at the same two bands;
- Divergence between the two slopes distinguishes optically thin ($\alpha_{thin} = \alpha_{Planck} + \beta$) and optically thick ($\alpha_{thick} \approx \alpha_{Planck} \leq 2$) regimes;
- Flux calibration errors (~5%, both bands) propagated in quadrature with map rms, assumed independent between bands [5];

Results

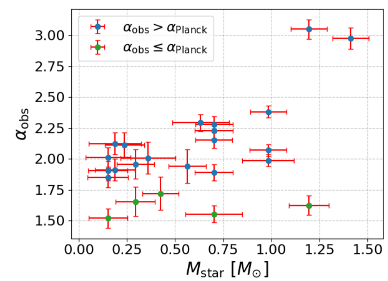

Figure 1: α_{Planck} vs M_{star} for the 24 systems in the Upper Sco sample.

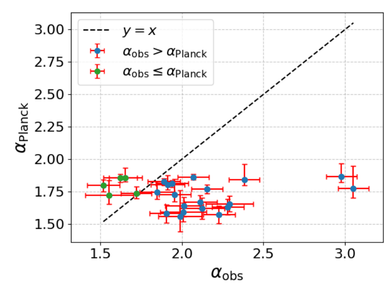

Figure 2: α_{Planck} vs α_{obs} for the sample with y = x line shown for reference.

Figure 1

- α_{obs} shows a weak trend with increasing M_{star} but with large scatter that is driven by two datapoints;
- The five sources identified as optically thick (green) fall at the bottom of the scatter;
- This is consistent with disk geometry and optical depth suppressing their spectral index rather than grain growth.

Figure 2

- Using $\beta = \alpha_{obs} - \alpha_{Planck}$ as a proxy for grain size, the optically thin sources with α_{obs} > 2.5 systematically lie below the y=x line (β < 1), indicating grain growth to mm sizes;
- The optically thick subset clustering above the line ($\alpha_{obs} \leq \alpha_{Planck}$) where beta is not a reliable indicator of grain growth – motivating the full optically-thick radiative transfer treatment with self-scattering for interpretation.

Future Work

- The full sample will be modeled with RADMC-3D under varying scattering treatments, each tailored to the individual stellar and disk parameters in each system;
- Test whether self-scattering can reproduce the low observed fluxes and corresponding low α_{obs} seen in the optically thick disks;
- Determine whether the low spectral indices are driven by genuine grain growth or scattering-suppressed millimeter emission.

References

[1] Barenfeld et al. 2016, ApJ, 827, 142
[2] Manara, Morbidelli, & Guillot 2018, A&A, 618, L3
[3] Zhu et al. 2019, ApJL, 877, L18
[4] Liu 2019, ApJL, 877, L22
[5] Garrett 2020, M.S. Thesis, CSU Northridge
[6] Feiden 2016, A&A, 593, A99