Probing the Magnetic Field Structure of the Protoplanetary Disk in HD 163296

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Introduction

Magnetic fields play a key role in star and planet formation within protoplanetary disks. Polarization is typically interpreted as tracing magnetic field lines via magnetically aligned dust grains. However, recent studies show that self-scattering by large dust grains can produce significant polarization, complicating this interpretation.[1] To extract the magnetic field structure, we analyze 870 μm ALMA polarization data from the disk around HD 163296, a young Herbig Ae star.

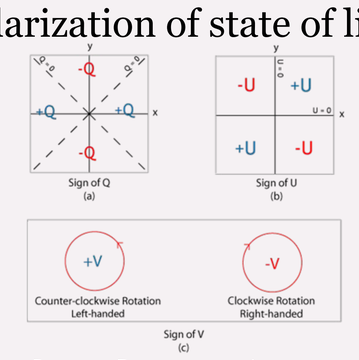
We separate polarization into components from dust self-scattering and magnetic alignment. Self-scattering polarization is simulated with RADMC-3D, and the remaining signal is used to trace magnetic field morphology, which we then compare with theoretical models.

Background Theory

Polarization & Stokes Parameters

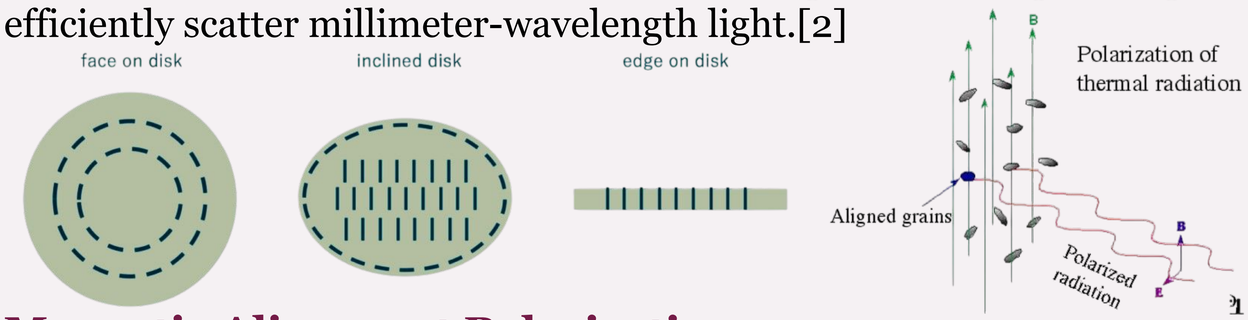
We use Stokes Parameters to represent the polarization of state of light:

- ★ I = total intensity
- ★ Q = horizontal/vertical polarization
- ★ U = diagonal polarization
- ★ V = circular polarization



Self-Scattering Polarization

Self-scattering refers to polarization produced when dust grains scatter their own thermal emission. This occurs when grains are large enough to efficiently scatter millimeter-wavelength light.[2]



Magnetic Alignment Polarization

Magnetic alignment polarization arises when elongated dust grains align with the magnetic field, making their thermal emission becomes polarized perpendicular to the magnetic field direction.[3]

Data & Method

HD163296 polarization data at a wavelength of 870 μm from ALMA archive.

Location: Sagittarius, 122 pc from Earth

Mass: 2.3 M⊙

Radius: 1.66 R⊙

Temperature: 9330 K

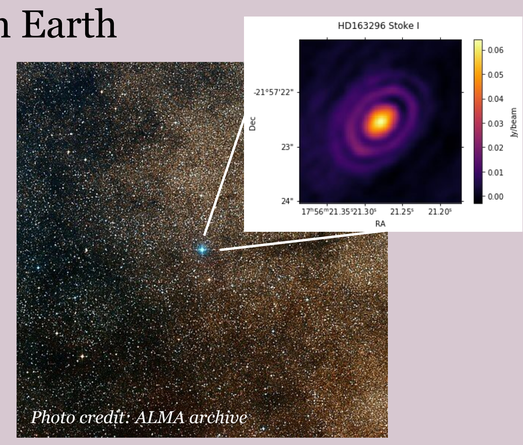
Dust Disk Radius : ~200 AU

Inclination: 46.95°

Position Angle: 47.63°

Formation Stage: Class II / III

Disk Features: Multiple ring-like structures and gaps

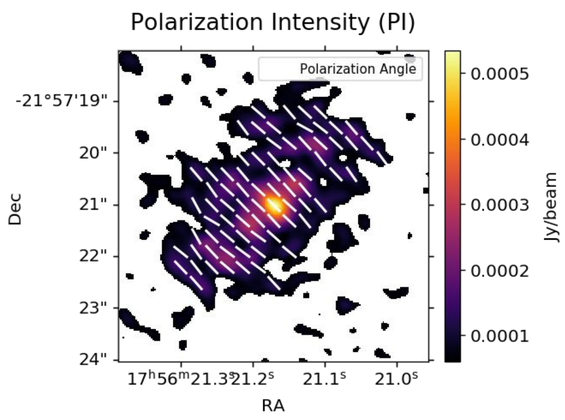


Compute polarization angle (PA) by Stokes I, Q, U data → Assume central PA comes from self-scattering → Separate polarization components into self-scattering and magnetic alignment → Estimate residual polarization attributed to magnetic alignment and infer magnetic field structure

Build disk model (RADMC-3D) and simulate polarization from self-scattering

Result & Discussion

Polarization Intensity & Polarization Angle



$$\begin{cases} PI = \sqrt{Q^2 + U^2} \\ PA = \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right) \end{cases}$$

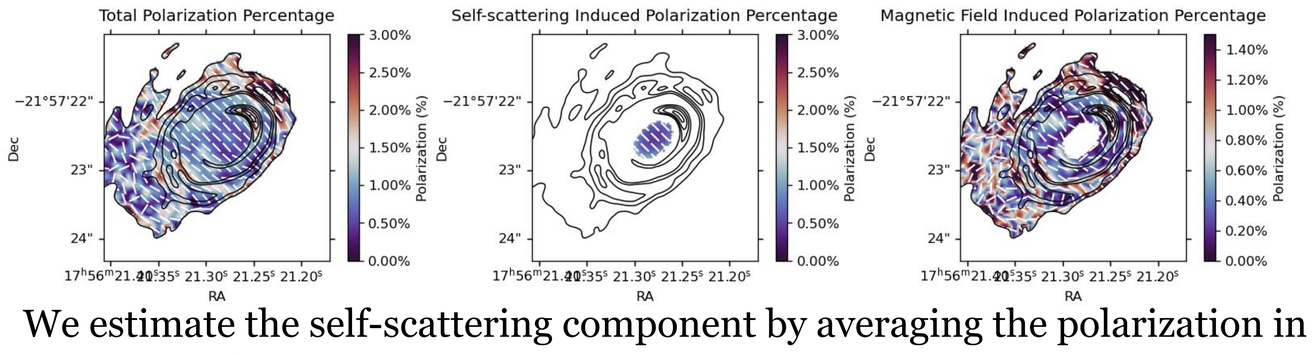
White lines display the PA, which is parallel to the miner axis of ellipse of protoplanetary disk. And it indicates that the dust emission polarization is dominated by self-scattering.

Polarization Percentage

$$Q_{total} \pm \sigma_Q = k \times Q_{self,avg} + Q_{mag}$$

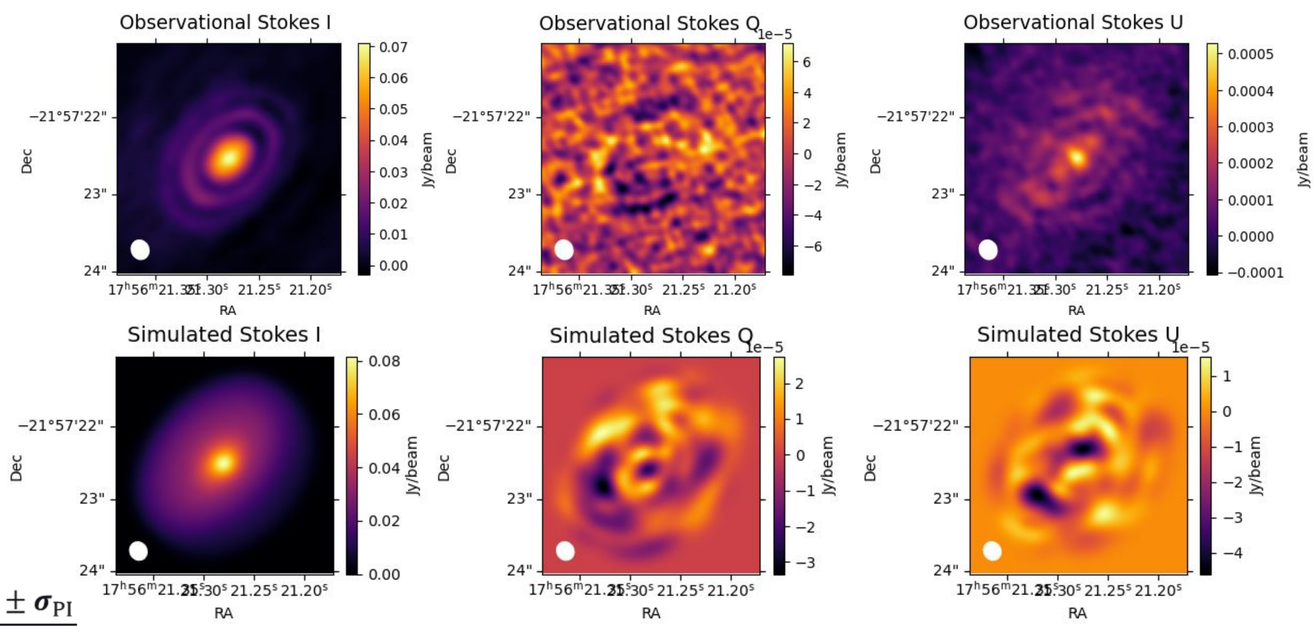
$$U_{total} \pm \sigma_U = k \times U_{self,avg} + U_{mag}$$

$$k = (I \pm \sigma_I)/I_{avg} \qquad Polarization\ \% = \frac{\sqrt{Q^2 + U^2} \pm \sigma_{PI}}{I}$$

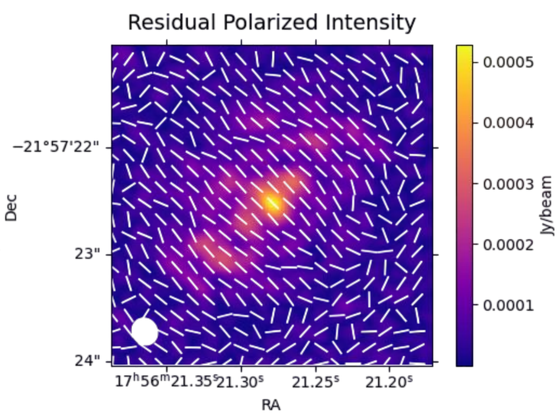


We estimate the self-scattering component by averaging the polarization in the central ellipse and scaling it by a factor k. After subtracting this from the total Stokes Q and U, the residual is attributed to magnetic alignment, yielding a polarization fraction of approximately 0.2 ~ 1.4 %. White lines show polarization angles, revealing a radial pattern consistent with magnetic field induced polarization, which is the expected result.

Observational / Simulated Stokes Images



Residual Polarization



We subtract simulated Stokes Q and U from observations to obtain residual polarization. White lines indicate polarization angles, showing a pattern similar to observations. The discrepancy likely arises from the current disk model, which lacks clear ring-gap structures. Future work will refine the model to better match observations and recover the magnetic field structure.

Reference

[1]Dent, W. R. F., et al. "Submillimetre dust polarization and opacity in the HD163296 protoplanetary ring system." Monthly Notices of the Royal Astronomical Society: Letters 482.1 (2019): L29-L33.

[2] Ohashi, François. "Radial variations of grain sizes and dust scale heights on the protoplanetary disk of HD 163296." ALMA2019: Science Results and Cross-Facility Synergies (2019): 49.

[3]Lazarian, Alex. "Tracing magnetic fields with aligned grains." Journal of Quantitative Spectroscopy and Radiative Transfer 106.1-3 (2007): 225-256.