Magnetic Fields and Dust Physics with SOFIA/HAWC+

Le Ngoc Tram

Max-Planck-Institute for Radio Astronomy, Bonn, Germany
nle@mpifr-bonn.mpg.de

April 22, 2024

Dust Polarization to Characterization of Magnetic Fields

- **Zeemann effect** (radio)
  - Advantage: line-of-sight and position-of-sky B-field,
    cold gas → star-formation studies
  - Disadvantage: challenge in calibrating and telescope time.
- **Faraday rotation** (radio)
  - Advantage: line-of-sight B-field
  - Disadvantage: only for ionized gas → less relevant to SF studies
- **Synchrotron polarization** (radio)
  - Advantage: regular/total B-field
  - Disadvantage: high-energy particles → less relevant to SF studies
- **Dust polarization** (optical/NIR and FIR/sub-mm)
  - Advantage: position-of-sky B-field (2D B-field)
    + inclination angle (3D B-field)
    dust → relevant to star-formation studies
  - Disadvantage: no line-of-sight B-field.

Dust Polarization to Characterization of Interstellar Dust

- **Essential "ingredients"** in various astrophysical/astrochemical processes
- **ISM's indicators** of structures, density and mass
- **Important role** in formation of stars and planets
  - source of heating, cooling, enhancement of molecular-formation rate, etc.
  - regulation of the system dynamics

➡ Characterization of dust's physical properties and chemical composition?

- Dust Polarization provides a valuable tool to assess these information

Dust Polarization Observations to Magnetic Field

Method Outline

Polarization Angle (Polarization Orientation) → B-field orientation

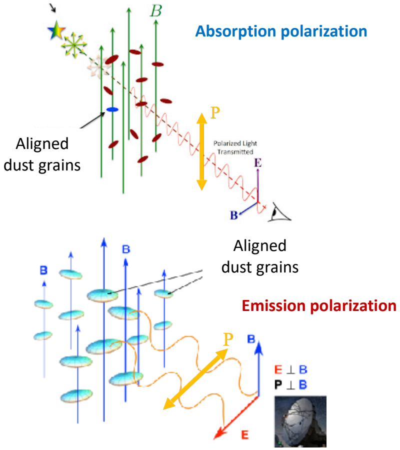
$$\theta = \frac{90}{\pi}\mathrm{arctan2}(\frac{\mathrm{U}}{\mathrm{Q}}) \quad \text{(degree)}$$

- Stokes Q and U are observed quantities

Polarization Angle + non-thermal broadening → B-field strength

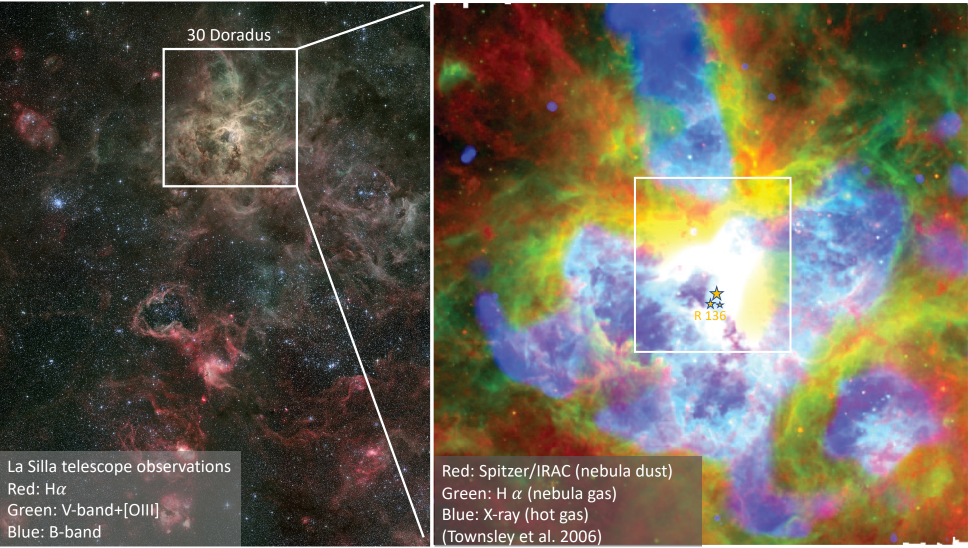
- resolved velocity profile is incorporated

"Ideal" Grain Alignment: Dust Pol. $\rightarrow$ Magnetic Field

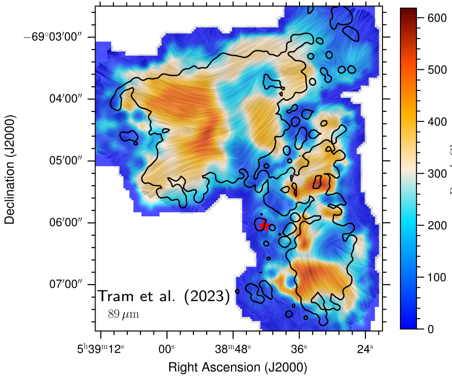


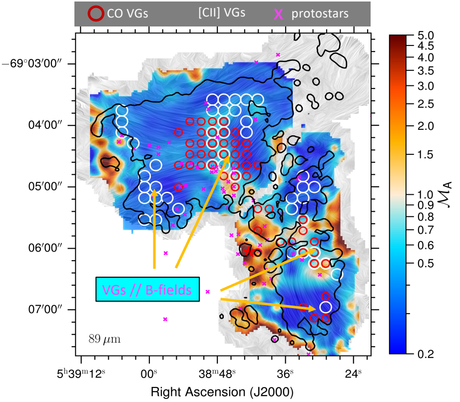
- Absorption pol. $\parallel$ to B-fields
  - Pol. vectors $\rightarrow$ B_{POS} morphology
  - Observable at UV-NIR wavelengths
- Emission pol. $\perp$ to B-fields
  - Rotating the pol. vectors by 90^o $\rightarrow$ $B_{\rm POS}$ morphology
  - Observable at FIR-Submm wavelengths
- B-strength:
  - "Tradition"
    - Davis 1951; Chandrasekhar-Fermi 1953
  - "Improvement"
    - Falceta-Gonçalves et al. 2008
    - Hildebrand et al. 2009; Houde et al. 2009
    - Skalidis & Tassis 2021
    - Lazarian et al. 2022

A Case Study of 30 Doradus



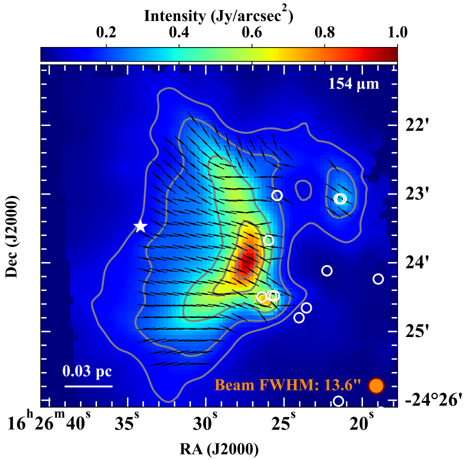
A Case Study of 30 Doradus



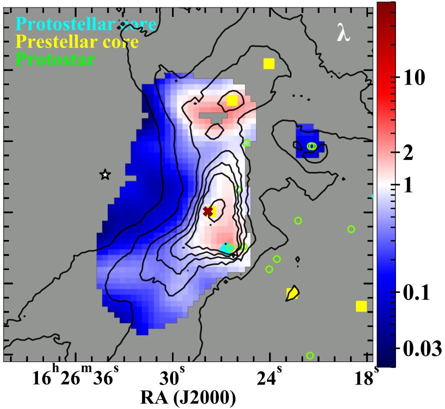


- Complex but ordered B-field morphology
- B-field strength varies across the cloud
- Strong B-field
- Supporting cloud against the R 136 feedback
- Majority of cloud is sub-Alfvénic
- Majority of cloud is sub-critical
- Turbulence helps to trigger SF

A Case Study of Ophiuchus-A cloud



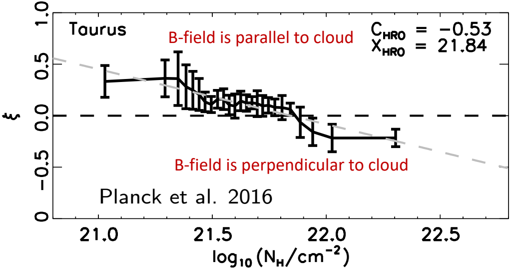
$$[\lambda] = [\text{gravity}]/[\text{B}-\text{field}]$$

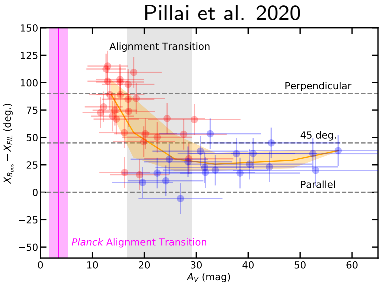


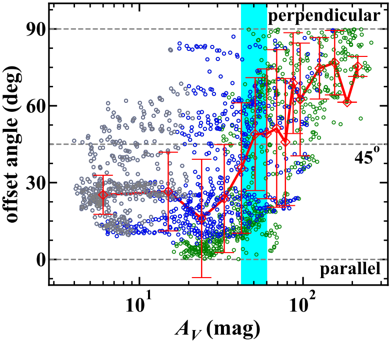
- B-field morphology → the MC's flat-shape
- Star formation occurs in $\lambda > 1$

Santos et al. 2019
Lê, Tram et al. (sub.)

Variation in B-field Orientation







Relative orientation between B-field and cloud

- Planck era: $B_{||}$ $(A_{\rm V} \leq 3) \leftrightarrow B_{\perp}$ $(A_{\rm V} > 3)$
- Serpens South: $B_{||}$ $(A_{\rm V} \geq 21)$
- Oph-A: $B_{\perp}$ $(A_{\rm V} > 40)$

Dust Polarization to Dust Properties

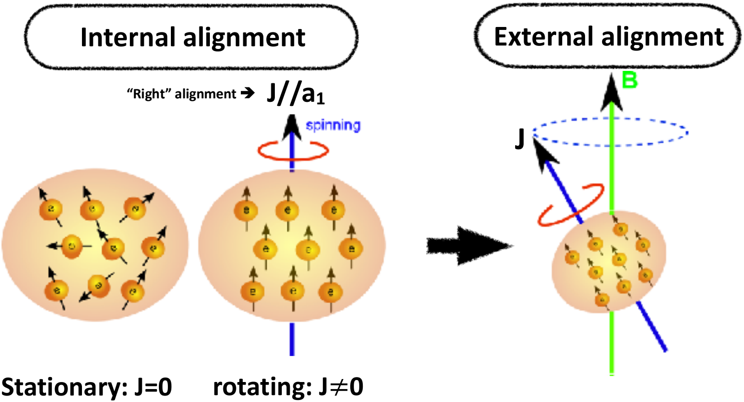
Method Outline

Polarization degree = Dust's intrinsic properties + ISM properties

Polarization degree : $p(\%) = 100 \times \frac{\sqrt{U^2+Q^2}}{I}$ (observable quantity)

- Dust's intrinsic properties : shape, size-distribution, composition, magnetic properties
- ISM properties : density, temperature, radiation, B-field, etc.
  ⚠ a "complete understanding" of grain alignment physics is required!

Grain Rotation and Alignment Mechanisms[1]

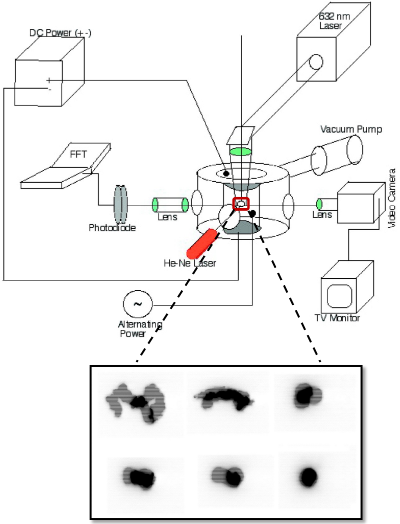


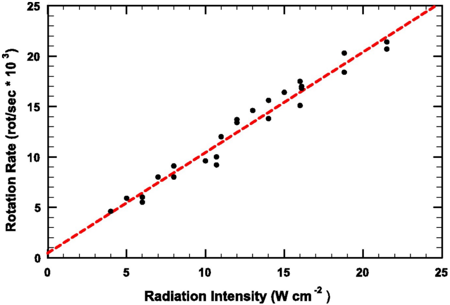
Radiative Torques (RATs) is the leading mechanism

(Dolginov & Mitrofanov 1976; Draine & Weingartner 1996; Lazarian & Hoang 2007)

[1] Only considering paramagnetic grains (e.g., astrosilicate)
Disregarding diamagnetic grains (e.g., carbonaceous)

Laboratory Experiments on Rotation of Interstellar Dust Grains by Radiation

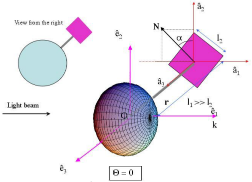


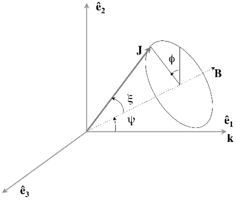


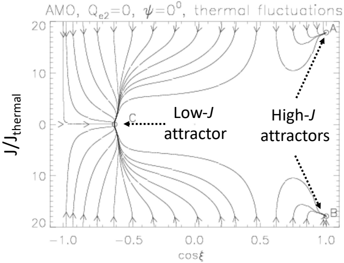
Abbas et al. 2004

Modelings on Rotation of Interstellar Dust Grains by Radiation

Analytical model (AMO)

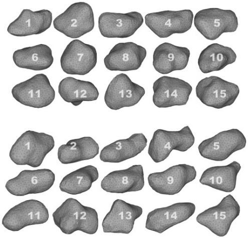






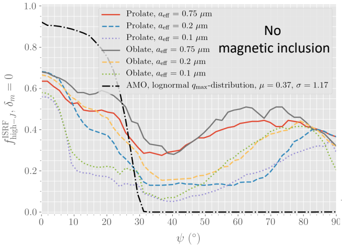
Lazarian & Hoang, 2007a

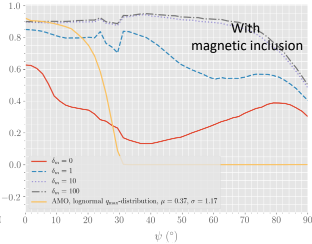
Numerical model



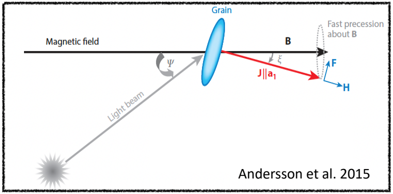
Herranen et al. 2021

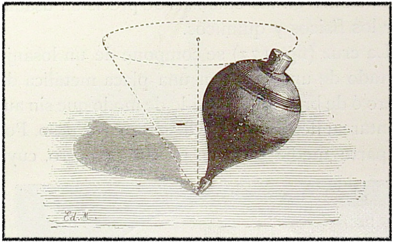
Fraction at high-J





RAT-A Theory in a Nutshell

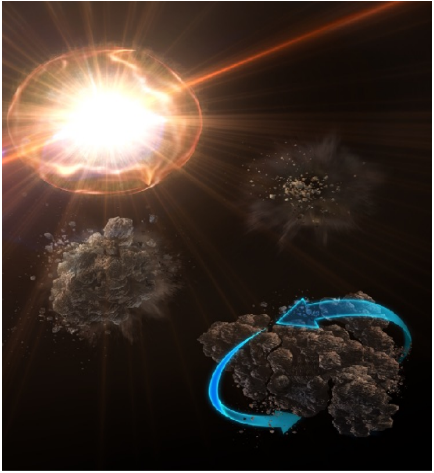




- Anisotropic radiation field causes irregular grains to rotate (Dolginov & Mitrofanov, 1976).
- Rotation damped by gas collisions and dust re-emission
- Internal alignment due to Barnett relaxation (Barnett, 1909)
- Alignment with external B-field due to Larmor precession and "F" component of RAT.

➡ RAT's predictions are confronted by observations: diffuse to MCs to SFRs (e.g., Andersson et al. 2015; Tram & Hoang, 2022)

Radiative Torque Disruption (RAT-D) Mechanism



Hoang, Tram et al. 2019, Nature Astronomy
Hoang, 2020
Lazarian & Hoang, 2021
Tram & Hoang, 2022

Table 2 | Characteristic timescales of dust destruction by different mechanisms

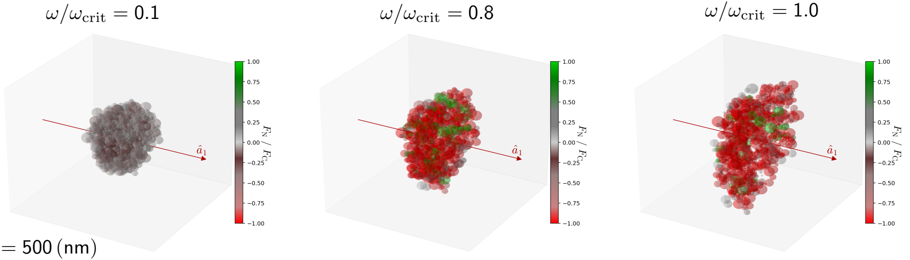
Mechanisms	Timescales (yr)
RATD	$1.0a_{-5}^{-0.7}\bar{\lambda}_{0.5}^{1.7}U_6^{-1}S_{\rm max,9}^{1/2}$
Thermal sputtering	$9.8\times10^3 a_{-5}n_1^{-1}T_6^{-1/2}(0.1/Y_{\rm sp})$
Non-thermal sputtering	$5.7\times10^3\hat{\rho}a_{-5}n_1^{-1}v_{\rm drift,3}^{-1}(0.1/Y_{\rm sp})$
Grain–grain collision	$7.6\times10^4\hat{\rho}a_{-5}n_1^{-1}v_{\rm drift,3}^{-1}$

$a_{-5}=a/(10^{-5}\,{\rm cm})$, $U_6=U/10^6$ $S_{\rm max,9}=S_{\rm max}/(10^9\,{\rm erg\,cm^{-3}})$ $n_1=n_{\rm H}/(10\,{\rm cm^{-3}})$, $T_6=T_{\rm gas}/(10^6\,{\rm K})$ $v_{\rm drift,3}=v_{\rm drift}/(10^3\,{\rm km\,s^{-1}})$, and $Y_{\rm sp}$ is the sputtering yield.

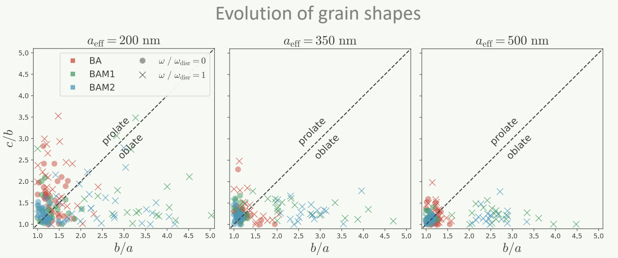
- RAT-D: fragmentation of large grains
  → upper-cutoff of the size-distribution
  → impact on dust absorption, emission, polarization, and surface chemistry
- RAT-D is far more efficient for $a > 0.1\,\mu$m and $U \gg 1$ ($U = u_{\rm rad}/u_{\rm ISRF}$)
- Disruption efficiency depends on the gas density, radiation strength, and grain porosity

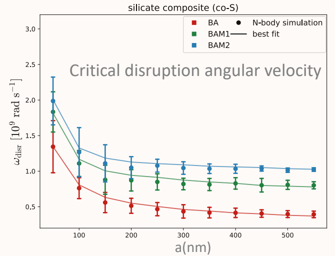
Simulations on Disruption of Porous Dust

Reissl et al. 2023

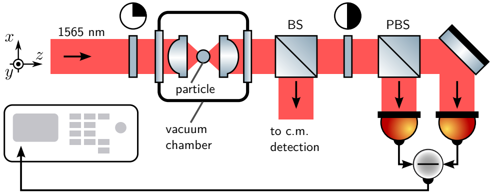


a = 500 (nm)

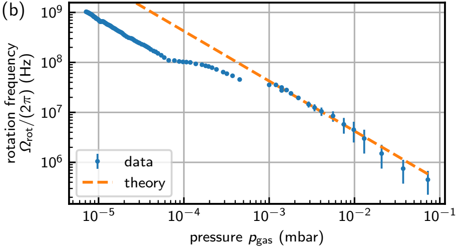




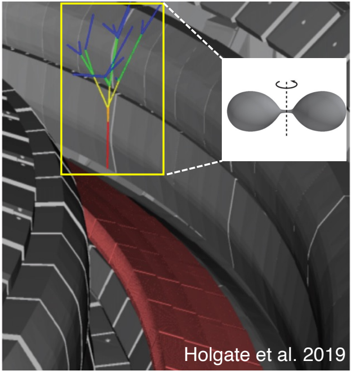
Laboratory Experiments on Disruption of Dust



Ahn et al. 2018
Reimann et al. 2018



Grain angular momentum gained by interaction with the laser field



To disrupt: 10 µm tungsten droplet
(surface tension 2.5N m^{-1} and density 17600 kg m^{-3})
Least angular velocity: 6 x 10^5 s^{-1}

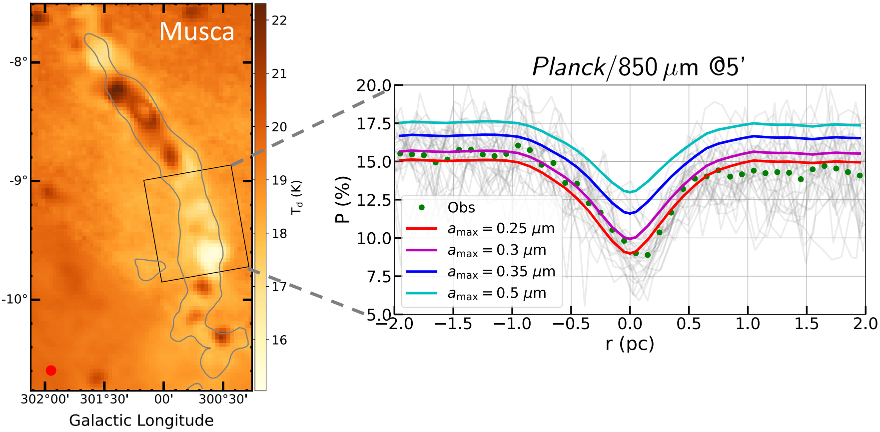
Gain angular momentum from gyrating particles in the surrounding plasma

Advancements in Computational Models

DustPOL[2] (Lee et al. 2019, Tram et al. 2021)	POLARIS+[3] (Giang, Hoang, Kim & Tram, 2023)
– RAT-A, MRAT and RAT-D	– RAT-A, MRAT and RAT-D
//	– dust self-scattering
– multi-wavelength	– multi-wavelength
– perfect alignment	– More realistic alignment
– uniform B-field (on POS and inclined)	– arbitrary B-field (e.g., from MHD)
– optically thin emission	– radiative transfer
– single-dish obs.	– single-dish and interferometry obs.

[2] https://github.com/lengoctram/DustPOL
[3] Initially developed by Reissl et al. 2016

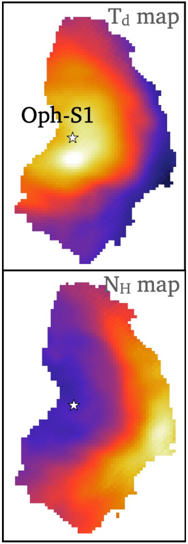
Musca Filament: *Planck* vs. DustPOL



Bich Ngoc, Diep, Thiem and Tram (submitted)

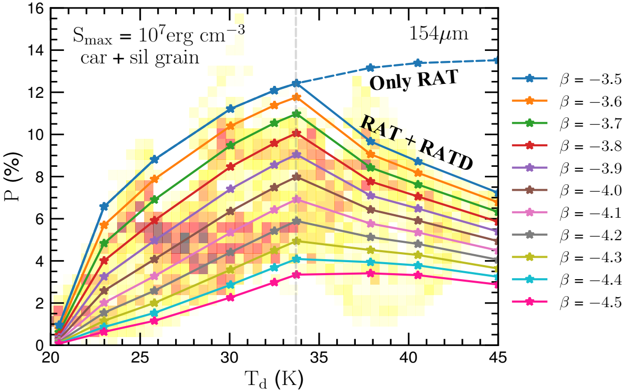
Ophiuchus Cloud: SOFIA/HAWC+ vs. DustPOL

ρ Oph-A cloud



Santos et al. (2019)

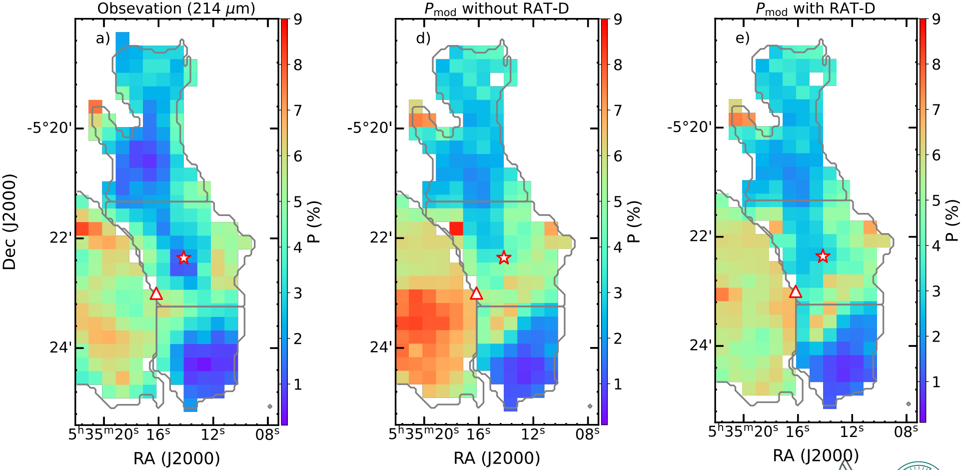
SOFIA/HAWC+ @14"



Tram et al. (2021a)

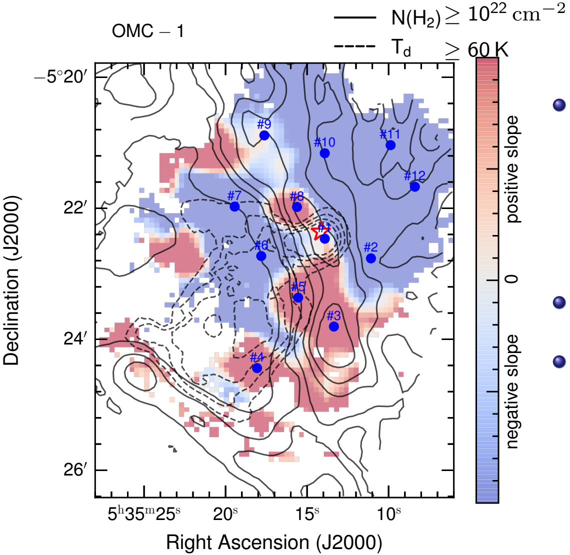
OMC-1 Cloud: SOFIA/HAWC+ vs. DustPOL

HAWC+ observation | RAT-A + B-tangling | RAT-A+RAT-D+B-tangling



Bich Ngoc, Diep, Thiem and Tram (submitted)

Multiple-wavelength Dust Polarization: OMC-1

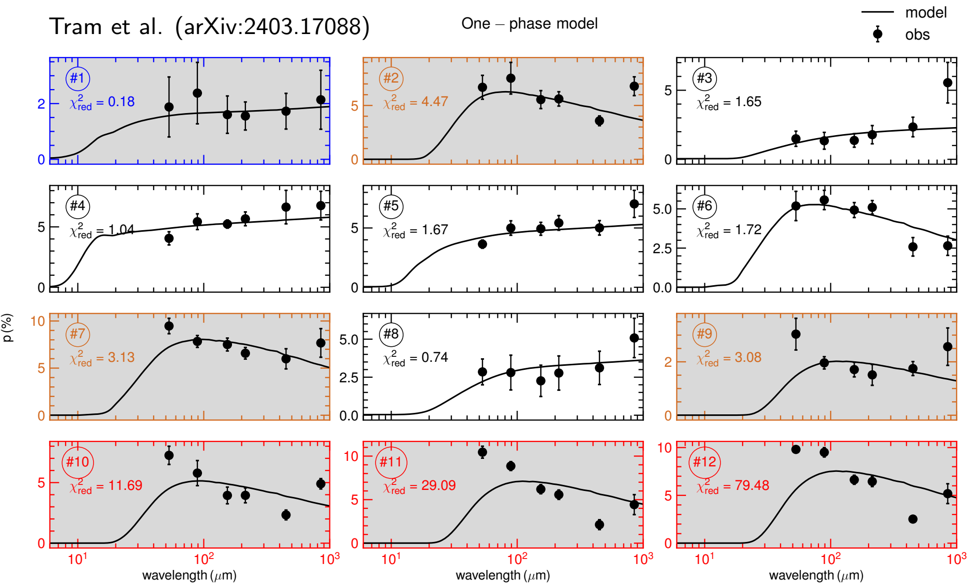


- pol. spectrum
  - 54, 89, 154, 214 μm with SOFIA/HAWC+
  - 450, and 850 μm with JCMT/Pol-2
- Pos. spectrum in dense region
- Neg. spectrum in warm region

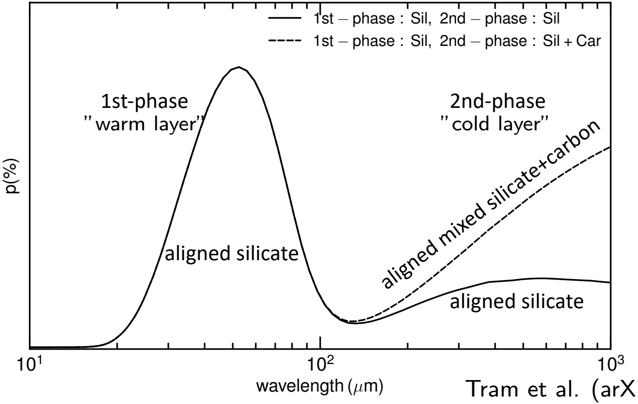
Tram et al. (arXiv:2403.17088)

SOFIA/HAWC+ and JCMT/POL-2 vs. DustPOL

Tram et al. (arXiv:2403.17088)



Improvement of DustPOL: One-layer → Two-layer model

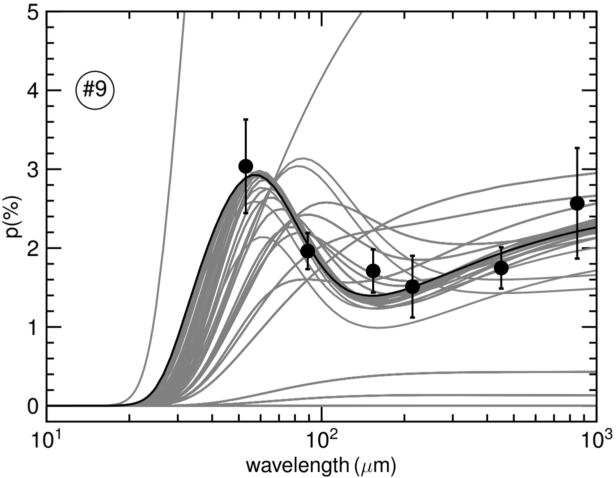


Tram et al. (arXiv:2403.17088)

We developed a two-layer dust model (two-phase) along LOS:

- 1st-phase: "warm" dust
- 2nd-phase: "cold" dust
- assumption: optically thin emissions in both phases

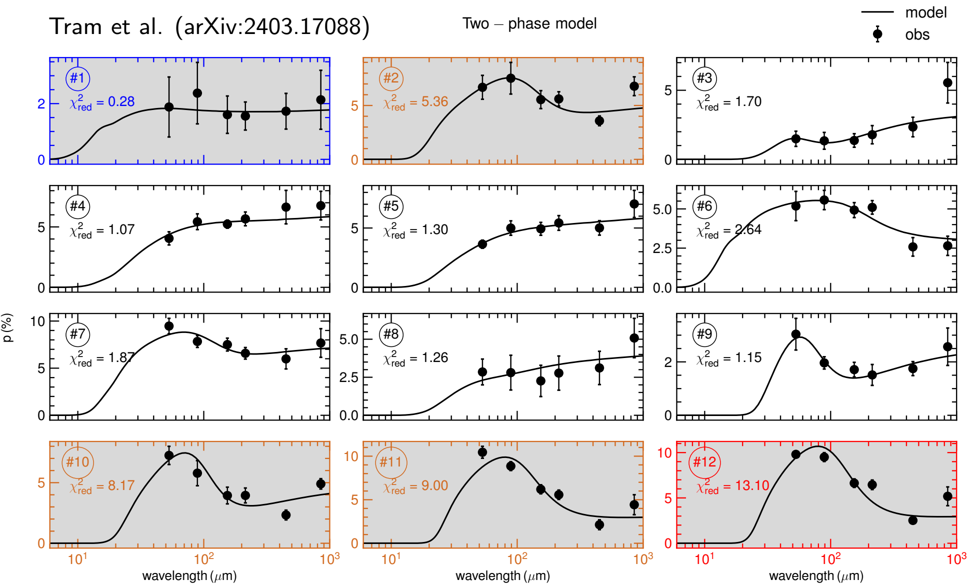
Example of Two-layer DustPOL Fitting



Two-phase DustPOL fits better than the one-phase

SOFIA/HAWC+ and JCMT/POL-2 vs. two-layer DustPOL

Tram et al. (arXiv:2403.17088)

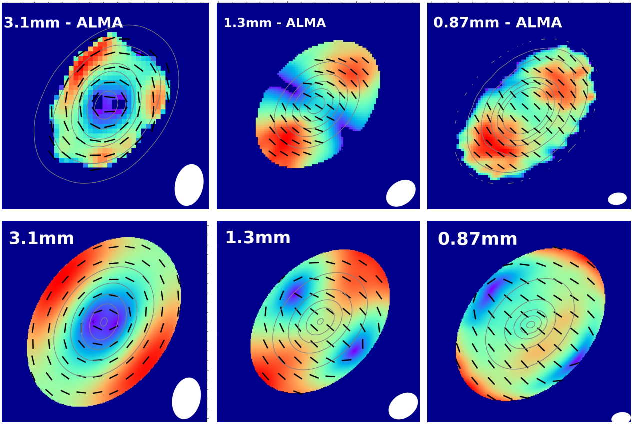


Protoplanetary Disk HLTau: ALMA vs. POLARIS+

"Smooth" Disk Physical Structure

Observations (ALMA)

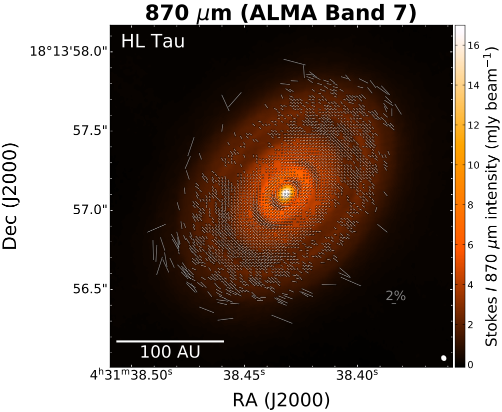
Simulations (POLARIS+)



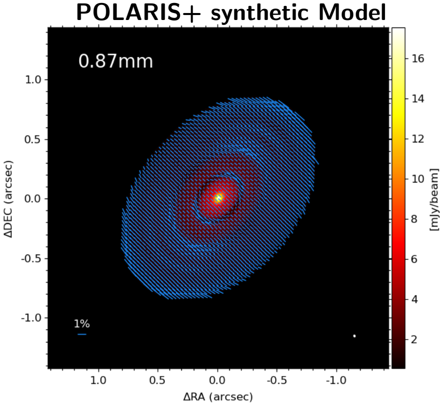
Nguyen Tat et al. 2024

Protoplanetary Disk HLTau: ALMA vs. POLARIS+

"Ring+Gap" Disk Physical Structure



Stephens et al. 2023 (Nature)



Nguyen Tat et al. 2024

Dust Polarization to 3D Magnetic Field

Method Outline

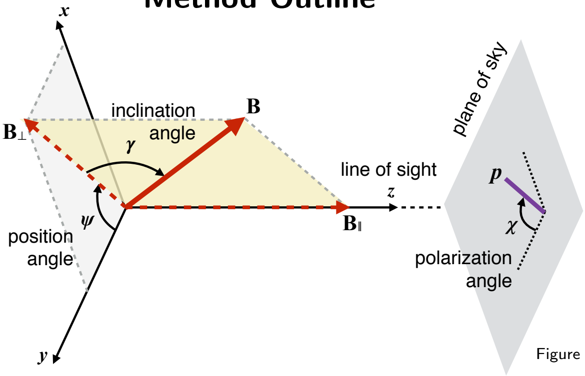


Figure from Chen et al. 2021

- polarization angle → plane-of-sky B-field (2D)
- polarization degree → B-field's incl. angle γ (3D)

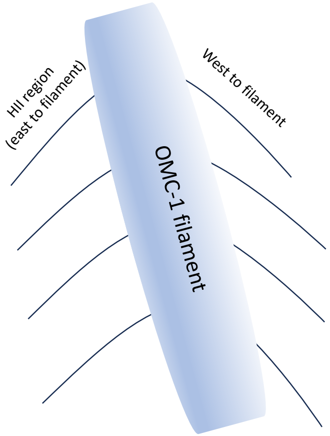
3D Magnetic Field in OMC-1

Two-phase model + MRAT-A theory[4]

Regions	$\gamma(^o)$	location
#1	47	Main filament
#3	49	Main filament
#8	50	Main filament
#9	24	Main filament
#5	56	HII-filament border
#4	40	HII (East to filament)
#6	76	HII (East to filament)
#7	76	HII (East to filament)
#2	33	West to filament
#10	34	West to filament
#11	36	West to filament
#12	38	West to filament

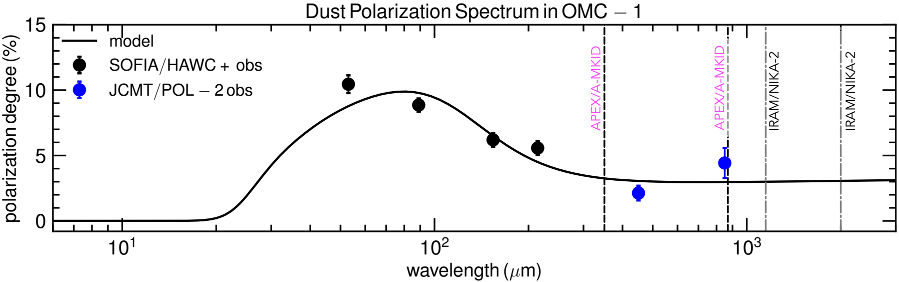
bow-shape B-field in OMC-1

Tram et al. (submitted)



[4]with iron inclusion

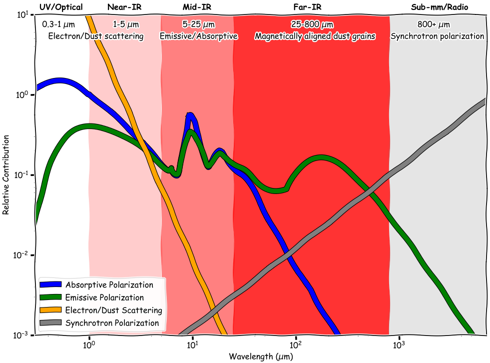
Request for Future Observatories: Dust Polarimetry at FIR



- The recent and the forthcoming polarimeters at (sub)millimeter wavelengths (JCMT/POL-2, APEX/A-MKID, IRAM/NIKA-2, etc.) will increase the model's precision and provide better understanding of the dust polarization physics.
- However, in the future, the lack of FIR polarization data could lead to a biased interpretation.

Request for Future Observatories: Dust Polarimetry at MIR

Toy model taken from E. Lopez-Rodriguez



- Theories established for dust pol. at UV-NIR (absorption+scattering)
- Theories established for dust pol. at FIR-(sub)mm (emission+self-scattering)
- MIR dust pol. → unification of grain alignment physics

Conclusion and perspective

Conclusions

1. Dust polarization observation is a valuable tool for probing and characterizing interstellar B-field (2D and possibly 3D)
2. Dust polarization observation provides valuable tools to investigate the fundamental of interstellar dust, using the RAT paradigm (RAT-A + RAT-D)
3. Multiple wavelength observation of dust polarization is logically a next crucial step
4. The theories of grain alignment and dust polarization have been dynamically improved and verified, thanks to SOFIA/HAWC+ observations
5. The role of the B-field in regulating the evolution of interstellar clouds and embedded star formation activities has been extensively explored, thanks to SOFIA/HAWC+ observations

Perspectives

1. Alignment of carbonaceous grains (Hoang, Minh & Tram 2023)
2. Unification of techniques for constraining the 3D B-field from dust polarization obs.
3. Exploring the SOFIA archival data + APEX + JCMT + IRAM
4. MIR and FIR dust polarimetries are fundamentally required (multiple bands are more desirable)

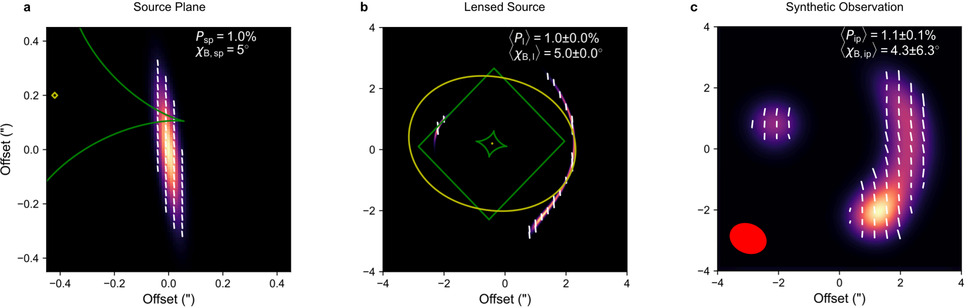
Thank you very much for your attention!

Thanks SOFIA!

The studies using SOFIA/HAWC+ are ongoing...

Back-ups

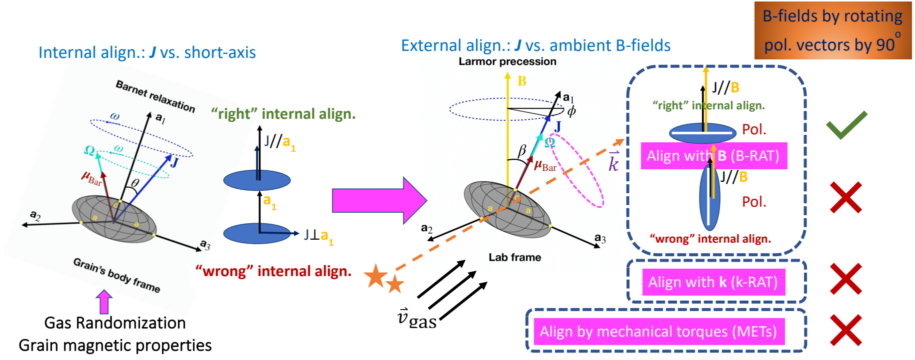
High-redshifted Galactic Magnetic Fields with ALMA



Geach et al. 2023, Nature

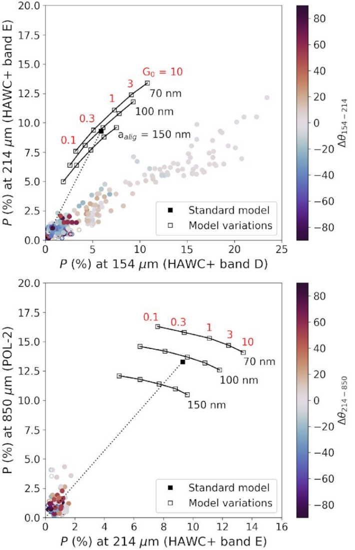
- Gravitationally lensed galaxy 9io9 at z=2.553,
- The polarized emission arises from the alignment of dust grains with the local magnetic field,
- 5kpc-scale ordered magnetic field with strength of $\simeq 500\mu$G.

"Realistic" Grain Alignment: Dust Pol. vs. Magnetic Field



- Dust polarization does not always trace B-field
  - Diffuse + MC: likely a reliable tracer (reviewed in Andersson+2015; Tram & Hoang 2022)
  - Cores/Disks: unlikely a reliable tracer [warning!] (details in Hoang, Tram et al. 2022)
- Dust polarization → B-field with caution

Multiple-wavelength Dust Polarization: pol. fraction ratio



Obs:
pol. degree ratio
Model:
Guillet et al. 2018

... models failed to reproduce the observations, even when parameter variations are included ...
(Fanciullo et al. 2022)

Dust Polarization Spectrum in Different Scales