The far-infrared polarization spectrum of Rho Ophiuchi A from HAWC+/SOFIA observations

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Magnetic Fields and Star Formation

- Role of magnetic fields in star formation
- Interstellar polarization from dust emission
- How to interpret polarization maps? Indirectly traces magnetic fields
  - Grain alignment

Magnetic fields in the Milky Way mapped through observations of interstellar polarization

Credits: ESA, Planck Collaboration
Outline

• The Rho Oph A molecular cloud

• Background on interstellar polarization spectrum and main science goals

• HAWC+/SOFIA Observations of Rho Oph A and polarization maps

• Evaluation of polarization spectrum spatial trends

• Comparison with a simple cloud model

• Upcoming work

• Conclusions and final remarks
Rho Oph A Molecular Cloud

- Rho Oph A: ~130 pc
- Warmed up by Oph S1 - massive B3-4 star
Rho Oph A Molecular Cloud

• Active star-forming region in Rho Ophiuchi (L1688)
  • Numerous YSO’s at different evolutionary stages, many of them present infrared excess at H-Ks (near-infrared bands)

• Different surveys also revealed a population of starless cores (Motte, Andre, & Neri 1998, Pattle et al 2015)

• Rho Oph A - extinction levels near the core can reach $A_v > 100$ mag
Rho Oph A Molecular Cloud / Oph S1 star

• Cloud morphology: 70 microns emission (Herschel): concentric arc-shaped filaments – centered on the Oph S1 star:
  • Dominating radiative/heating source for dust emission Rho Oph A (as can be seen from Spitzer and Herschel images):
  • B3-4 massive star (Hamaguchi et al. 2003, Andre et al 1992, 1988);
  • Surrounded by a compact HII region (~20 arcsec)
  • Indications of triggered star formation around S1 (Motte, Andre & Neri 1998)

Herschel PACS 70 micron map of Rho Oph A.

1.3 mm map from Motte, Andre & Neri (1998): six protostellar clumps seen at 1.3 mm formed by fragmentation in the compressed gas layer at the interface between the PDR and the Oph-A cloud core.
Background and main science goals

- Grain alignment/Radiative Torques (RATs) – fundamental connection between B-fields and polarization measurements
- Main goals: evaluate grain alignment efficiency through calculations of the polarization ratio $p_{\lambda_1}/p_{\lambda_2}$
Main science goals – FIR Polarization spectrum

• Why polarization ratio \( \frac{p_{\lambda_1}}{p_{\lambda_2}} \) and not just polarization degree \( p_\lambda \)?
  • Polarization degree \( p_\lambda \) – depends on inclination of \( \mathbf{B} \) along the line-of-sight
    … but the ratio \( \frac{p_D}{p_C} \) does not → map variations of grain alignment efficiency

• Polarization ratio traces the slope of the polarization spectrum. For Rho Oph A: bands D (154 µm) an C (89 µm):
  • \( \frac{p_D}{p_C} > 1 \): positive slope
  • \( \frac{p_D}{p_C} < 1 \): negative slope

• But, from the literature, there is not much consensus between observations and theory…
Main science goals – FIR Polarization spectrum

• What is the shape of the polarization spectrum in the far-infrared?
  - **Observed – negative slopes** (e.g., Vailancourt et al. 2012, Zeng et al. 2013):
    \[
    \left( \frac{dp}{d\lambda} \right)_{FIR} < 0
    \]

  Proposed explanation: mixture of cold and warm regions along LOS – assuming RATs **grain alignment**, hot regions are better aligned than cold regions;
  Since the hot regions with well-aligned grains will be relatively brighter than the cold regions at the shorter wavelengths, we expect shorter wavelengths to be more polarized – **negative slopes**
Main science goals – FIR Polarization spectrum

- What is the shape of the polarization spectrum in the far-infrared?
  - **Theory – positive slopes**
    (e.g., Bethell et al. 2007; Guillet et al. 2018):

  \[
  \left( \frac{dp}{d\lambda} \right)_{FIR} > 0
  \]

  Explanation: (1) larger-sized grains ($\geq 0.2 \mu m$) are relatively more efficiently aligned as compared to smaller-sized grains ($\approx 0.2 \mu m$) (Kim & Martin 1995, also predicted from the RATs grain alignment theory; e.g., Lazarian 2007); (2) Even when subject to a uniform radiation field, smaller grains are relatively warmer than larger grains (Li et al. 1999) – positive pol. spectrum slopes

- Pol. Spectrum in Rho Oph A:
  - Important test for grain alignment theory;
  - Additionally, connection between observations and theory;

Compilation of pol. spectrum observations (gray lines) compared to the dust grain models of Bethell et al. (2007) (green). Typically decreasing slopes observed in the FIR.

Polarization spectrum predictions from dust grain models by Guillet et al. (2018). Increasing slopes predicted in the FIR.
Rho Oph A – HAWC+ Observations

- HAWC+ Observations:
  - Band C: 89 µm
  - Band D: 154 µm

Main Goal: combine pol. bands C and D
- Slope of polarization spectrum – probe grain alignment efficiency
- Test Radiative Torques (RATs)

Column density map (based on Herschel)
- Peak extinction $A_V > 100$ mag
Column density and temperature maps

• Based on mod. black-body fits to Herschel (70, 100, 160 µm) data

• Serve as proxies for highly illuminated (warm, more diffuse regions exposed to Oph S1 radiation) and highly obscured regions (cold and dense);
Magnetic fields in Rho Oph A

Rho Oph A

Oph S1

B-field inferred

HAWC+ polarization map band C - 89 µm, ~7.8” beam size

Comparison of polarization angles bands C & D

Median = -0.7 deg; Std. Dev. = 1.86 deg

HAWC+ polarization map band D - 155 µm, ~13.6” beam size
Magnetic fields in Rho Oph A

- Slope of polarization spectrum: $R_{DC} = \frac{p_D}{p_C}$

Santos et al. (2019, ApJ 882 2)
Far-IR polarization spectrum

Map of $R_{DC} = p_D / p_C$

More diffuse $R_{DC} > 1$
Dense $R_{DC} < 1$

- Systematic dependence of polarization spectrum slope with cloud density

- Hypothesis: differences in grain alignment efficiency
  - outer (warm) grains, well aligned
  - inner (cold) grains, poorly aligned

Santos et al. (2019, ApJ 882 2)
Far-IR pol. spectrum: model vs. observations

• Very simple model:
  • Spherical dense core embedded in uniform background
  • Fit 7 model parameters based on Herschel data

• Transition radius $R_T$:
  • $r < R_T$: no polarized flux (no grain alignment) – **only free parameter**
  • Test for RATs
Far-IR pol. spectrum: model vs. observations

• Description of $p_D / p_C$ calculation for simple model

$$P_\lambda(x) = p_{\lambda,0} I'_\lambda(x)$$
$$p_\lambda(x) = P_\lambda(x)/I_\lambda(x)$$

$$I_\lambda(x) = \kappa_{250} \mu m_H \left( \frac{\lambda_0}{\lambda} \right)^\beta \int n(r) B_\lambda(T(r)) ds + I_{\lambda,b}$$

• The physical parameters used in the equations are chosen so that the model provides the best fit possible to the Herschel column density and temperature maps.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Determined Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>Core radius</td>
<td>0.074 pc</td>
</tr>
<tr>
<td>$N_b$</td>
<td>$\text{H}_2$ ambient column density</td>
<td>$5.7 \times 10^{21}$ cm$^{-2}$</td>
</tr>
<tr>
<td>$T_b$</td>
<td>Ambient dust temperature</td>
<td>30.7 K</td>
</tr>
<tr>
<td>$T_R$</td>
<td>Local dust temperature at the core edge ($r = R$)</td>
<td>38.9 K</td>
</tr>
<tr>
<td>$n_o$</td>
<td>$\text{H}_2$ number density at the core center ($r = 0$)</td>
<td>$6.4 \times 10^6$ cm$^{-3}$</td>
</tr>
<tr>
<td>$R_p$</td>
<td>Core Plummer radius</td>
<td>$0.244 R$</td>
</tr>
<tr>
<td>$T_o$</td>
<td>Local dust temperature at the core center ($r = 0$)</td>
<td>13.9 K</td>
</tr>
</tbody>
</table>
Comparing model with observations:

- Calculate $R_{DC}$ vs. log $N$ for different $R_T$ values: 0.3 $R$, 0.6 $R$ and 0.9 $R$
Far-IR pol. spectrum: model vs. observations

- The observed decrease of ~50% in $R_{DC}$ can be reproduced with the simple model.

- Decrease in grain alignment efficiency likely responsible for trends in polarization spectrum slope – support for RATs.

Santos et al. (2019, ApJ 882 2)

SOFIA Tele-Talks - September 2019
Far-IR pol. spectrum: model vs. observations

- Temperature dependence of $R_{DC}$

- The local temperature (from model) can serve as a proxy for the radiation intensity and can thereby be related to grain alignment efficiency.
Pol. spectrum comparison with dust grain models

- Lower column density end: $10^{21.5} < N \text{ (cm}^{-2}\text{)} < \approx 10^{22.0}$, mean $R_{DC} \approx 1.1$

- From Bethell et al. (2007) model (which probes similar column densities): $1.75 < R_{DC} < 2.0$
  - But model temperatures ($\approx 5–17 \text{ K}$) are much smaller than the observed around Rho Oph A ($\approx 30–40 \text{ K}$)
• **Draine & Fraisse (2009)** found $R_{DC}$ values between 1.4 and 2.6, which are also slightly higher than the mean values found in Rho Oph A for the lower column density areas.
  - But this model is valid for the diffuse ISM.
Pol. spectrum comparison with dust grain models

- **Guillet et al. (2018)** presents models for translucent clouds of $10^{21.0} < N \text{ (cm}^{-2}\text{)} < \approx 10^{21.5}$, i.e., somewhat smaller than Rho Oph A column density levels.

- Predicted polarization spectrum curves are significantly affected by the ISRF level.

- Models with higher ISRF levels show $R_{DC} \approx 1.1$ (black curves), while models with lower ISRF intensities show $R_{DC} \approx 20.0$ (blue curves).

- Somewhat small positive values of $R_{DC}$ for the diffuse component of Rho Oph A (as compared to dust grain models) might be due to the strong exposure to radiation from Oph ST.

Guillet et al. (2018) polarization spectrum models for a translucent cloud considering different levels of the interstellar radiation field (IRSF).
Far-IR pol. spectrum: model vs. observations

• Main conclusions and take-away points:
  • This analysis introduces a new method to probe the grain alignment efficiency in molecular clouds;

• Provided that a model is given for the studied cloud, one may test beyond which core depth, or below which local temperature, the grain alignment is no longer efficient, with no LOS inclination effects.

• Comparison between simple cloud model and observations provides support to the radiative-driven grain alignment mechanism (RATs)

• Connection between dust models and observations: first direct observation of positive inclinations in the FIR polarization spectrum
Continuing work: new polarimetric dataset

• Additional GTO dataset

Band A (53 μm) – green – new (centered on Oph S1)
Band C (89 μm) – red – more spatial coverage
Band D (154 μm) – white – same as before

• More spectral coverage including band A, better angular resolution – B-fields near Oph S1
Continuing work: new polarimetric dataset

- Polarization maps (B-fields):

Band A

Band C

Band D
Continuing work: new polarimetric dataset

• Line-integral-convolution maps:
Continuing work: new polarimetric dataset

- Distortion of B-fields around Oph S1
- Possibly due to expansion of UC HII region around the massive star
Continuing work: problems with current model

- Comparison between synthetic maps from spherical model and observations

- Best possible spherical model, but clear differences exist
Continuing work: new model

- New model, more realistic, by Liseau et al. (2015)
Final remarks

• First conclusive observation of systematic variations of the far-infrared polarization spectrum within an interstellar cloud.

• Consistent with reduced grain alignment efficiency in the core, based on very simple modeling of the cloud.

• New method to probe grain alignment efficiency. Grain alignment theory: critical connection between interstellar polarization and magnetic fields – crucial to understand star formation.

Thank you!