3D mapping of the magnetized ISM with starlight polarization

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B-mode from space
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‘The’ dust component

How to go from the simplest model to a plausible model?

Dust varies along line of sight

A 3D map of dust extinction from stars: Green et al. (2019)
Parametric modeling of ISM dust: a first approximation

- Assume uniform population of dust grains in uniform magnetic field

\[ Q_v = A^P \cos 2\chi \left( \frac{v}{v_0} \right)^\beta B_v(T) \]
\[ U_v = A^P \sin 2\chi \left( \frac{v}{v_0} \right)^\beta B_v(T) \]

Frequency dependence only by Modified Black-body

- Solve for all foreground model parameters
Parametric modeling of ISM dust: a first approximation

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\]

Frequency dependence only by Modified Black-body

- Solve for all foreground model parameters

What accuracy can we reach with this approximation?
WANTED: better approximation to dust modeling

When multiple clouds along the line of sight, single blackbody model assumption breaks down

\[ I_{\text{tot}} = I_1 + I_2 \]
\[ Q_{\text{tot}} = Q_1 + Q_2 \]
\[ U_{\text{tot}} = U_1 + U_2 \]

Multiple dust clouds in principle need to be taken into account ...


...but no consensus as to what the importance of the effect is for foreground subtraction
WANTED: better approximation to dust modeling

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Multiple dust clouds \textit{in principle} need to be taken into account ...


...but no consensus as to what the importance of the effect is for foreground subtraction

Answer depends on ISM properties!

Need to \textit{measure} ISM properties in 3D
Towards a better approach to dust modeling: starlight polarization

Dust grains aligned perpendicular to magnetic field lines act as a polarizer

Both types of radiation trace component of B perpendicular to line of sight
Towards a better approach to dust modeling: starlight polarization

Dust grains aligned perpendicular to magnetic field lines act as a polarizer

Both types of radiation trace component of B perpendicular to line of sight

BUT: stellar polarization traces signal only out to distance of star!
Starlight polarization not well-sampled

Planck @ 353GHz

Need orders of magnitude more stellar polarization measurements
A high-accuracy optical polarization survey

Measuring the polarization of millions of stars to tomographically map the ISM magnetic field

Starts in 2020!

Web: pasiphae.science
White paper arXiv:1810.05652

Partner Institutions
University of Crete (PI: K. Tassis)
Caltech
University of Oslo
Inter-University Center for Astronomy and Astrophysics
South African Astronomical Observatory
Key advances of PASIPHAE

Two 1-m telescopes (North + South)

Single-shot, wide field polarimeters (WALOPs)

0.5x0.5 deg Field of View

Excellent control of instrument systematics
(0.1% systematic uncertainty in p - unprecedented for wide-field stellar polarimetry)

Skalidis+2018, Ramaprakash+2019

Single-shot principle successfully implemented in precursor instrument

Robopol
A first look at PASIPHAE-like data

A path-finding survey for PASIPHAE with the RoboPol polarimeter

To observer

Cloud 1

Cloud 2

B₁

B₂

Deep optical polarization survey
The target region in HI

Effelsberg-Bonn HI Survey (Winkel+ 2016)
Two very different clouds along the same line of sight

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Stellar polarizations in 2D

PDF of polarization angle

Previously unknown intrinsically polarized sources

No indication of difference between regions by looking at polarization angles in 2D

Panopoulou+2019a
Looking into the line-of-sight dimension with Gaia distances

Panopoulou+2019a
Decomposing the polarization properties of the clouds

\[ \langle q_{\text{obs}} \rangle = 0 \]
\[ \langle u_{\text{obs}} \rangle = 0 \]

To observer

Cloud 1

Group 0

Group 1

Group 2

\[ \langle q_{\text{obs}} \rangle = \langle q_1 \rangle \]
\[ \langle u_{\text{obs}} \rangle = \langle u_1 \rangle \]

\[ \langle q_{\text{obs}} \rangle = \langle q_1 \rangle + \langle q_2 \rangle \]
\[ \langle u_{\text{obs}} \rangle = \langle u_1 \rangle + \langle u_2 \rangle \]
Statement of the problem

We wish to determine:

\[ q(x) = \begin{cases} 
0, & 0 \leq x < d_1 \\
q_1, & d_1 \leq x < d_2 \\
q_1 + q_2, & d_2 \leq x < d_3 \\
q_1 + q_2 + q_3, & d_3 \leq x < \ldots 
\end{cases} \]

Unknowns:

- \( N_{clouds} \) \text{ Number of clouds}
- \( d_1, d_2, d_3, \ldots \) \text{ Location of clouds}
- \( q_1, q_2, q_3, \ldots \) \text{ Cloud polarization properties}

(And Stokes \( u \) similarly)

To locate clouds look for a peak in the derivative of the polarization fraction \( p = \sqrt{q^2 + u^2} \)
We can detect the effect of the second cloud!

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Black points: Peak indicates second cloud
Red points: No peak in region where we don’t expect second cloud to contribute

Now we can decompose the polarization from each cloud...

Nearby cloud
Far cloud

The nearby cloud causes 5-6 times more polarization than the far cloud
The magnetic field orientation in each cloud

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The magnetic field orientation in each cloud

Clark & Hensley 2019
Dust temperature too varies along line of sight?

Other IVCs known to have higher dust temperature than local gas (Planck XXIV 2011)
Modeling dust emission from 2 clouds

1. The 2-cloud model:

\[ I_{\text{tot}} = I_1 + I_2 \]
\[ Q_{\text{tot}} = Q_1 + Q_2 \]
\[ U_{\text{tot}} = U_1 + U_2 \]

2. Stokes parameters for each cloud:

\[ I_{\nu}^{C_i} \propto c^{C_i} (\frac{\nu}{\nu_0})^{\beta^{C_i}} N_{H_i}^{C_i} B(\nu, T^{C_i}), \]

\[ Q_{\nu}^{C_i} = p_{\nu}^{C_i} I_{\nu}^{C_i} \cos 2\chi^{C_i}, \quad U_{\nu}^{C_i} = p_{\nu}^{C_i} I_{\nu}^{C_i} \sin 2\chi^{C_i}, \]

\[ c: \text{dust-to-gas mass ratio, } N_{H_i}: \text{HI column density,} \]
\[ T: \text{temperature, } C_i: \text{the } i\text{-th cloud, } \chi = \text{polarization angle (emission)} \]
Constraining the unknown parameters

Starlight $p$ is proxy for dust emission $P_{353}$

If we assume $P_{353}^C / P_V^C = P_{353}^C / P_V^{C_2}$ and $p(ν) \sim \text{const}…$ the only remaining unknowns are temperature, $β$

But also just from:

$$p = \frac{\sqrt{Q^2 + U^2}}{I_V} = \frac{\sqrt{(A Q)^2 + (A U)^2 \left(\frac{ν}{ν_0}\right)^β}}{A I \left(\frac{ν}{ν_0}\right)^β} B(νT)$$
Predicting the polarization angle at different frequencies

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Polarization angle with 2-cloud model:

\[
\chi_\nu = \frac{1}{2} \arctan \frac{r_\nu \sin 2\chi^C_1 + \sin 2\chi^C_2}{r_\nu \cos 2\chi^C_1 + \cos 2\chi^C_2}
\]

\[
r_\nu = \frac{P_\nu^{C_1}}{P_\nu^{C_2}} = \frac{I_\nu^{C_1}}{I_\nu^{C_2}}.
\]
Summary

Upcoming optical polarization survey & Gaia enables 3D B-field mapping

1st pathfinding demonstration of tomographic capabilities successful

Exciting future prospects for 3D modeling: starlight polarization, HI, dust extinction, MHD simulations...

Thank you