Relative Orientation of Magnetic Field and Cloud Structure in L1688

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Our Galactic Ecosystem: Opportunities and Diagnostics in the Infrared and Beyond
HAWC+/SOFIA Polarimetry in L1688: Relative Orientation of Magnetic Field and Elongated Cloud Structure

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Ingredients of Star Formation

- Gravity
- Turbulence
- Magnetic Field
Ingredients of Star Formation

Gravity

Turbulence

Magnetic Field

What is the exact role of the magnetic field in star formation?
Polarization by Emission

Interstellar dust → Grain alignment mechanism → Long axis is perpendicular to the magnetic field

Thermal emission is polarized orthogonal to the magnetic field

Infer the magnetic field orientation from polarization observations
Plane of Sky Magnetic Field Orientation

Figure 24 — Planck 2015 I. Results (2016)

Figure 5 — Fissel et al. (2016)

Quantity of Polarization Measurements!

Plane of Sky Magnetic Field Orientation
Plane of Sky Magnetic Field Orientation

Figure 1 — Chuss et al. (2019)
What can we do with this orientation information?
What can we do with this orientation information? compare with the cloud structure!
What can we do with this orientation information? compare with the cloud structure!

preferentially parallel

preferentially perpendicular
What can we do with this orientation information? compare with the cloud structure!

How would one measure this?
Histogram of Relative Orientations (HROs)

Parameter that quantifies this parallel vs. perpendicular alignment
Observations!

Analysis applied to ten molecular clouds in the Milky Way.

Consistent with a transition to no or perpendicular alignment

Figure 7 — Planck Int. Results XXXV
Planck Int. Results XXXV

Observations!

Compared with a set of simulations from Soler et al. (2013)

Molecular clouds consistent with trans- or sub-Alfvénic
Observations!

Clouds showed varying degrees of crossing from parallel to perpendicular.
Use HAWC+ on SOFIA to see if the trend continues to higher column densities.
High(er) Column Density Polarization

SOFIA/HAWC+
154 μm (Band D)
13.6 arcsecond

Inferred Magnetic Field Orientation

First Presented in Santos et al. (2019)
Low(er) Column Density Polarization

Planck
850 μm (353 GHz)
5 arcminute

Inferred Magnetic Field Orientation

Rho Oph A
Rho Oph E
Extending the HRO

SOFIA/HAWC+
154 μm
33.6 arcsecond

L1688

preferentially parallel

preferentially perpendicular

Planck
850 μm
5 arcminute

log_{10} \left( \frac{N_{\text{H}_2}}{\text{cm}^{-2}} \right)
Extending the HRO

SOFIA/HAWC+
154 μm
33.6 arcsecond

samples
only ~10%

L1688
preferentially parallel
preferentially perpendicular

Planck
850 μm
5 arcminute

log_{10} \left( N_{\text{H}_2} / \text{cm}^{-2} \right)
Extending the HRO - Sampling Uncertainty

Other regions of L1688 exist

i.e., Rho Oph C
Extending the HRO - Sampling Uncertainty

*samples only ~10%

the transition continues to hold at these higher column densities
Transition Column Density

Where the column density transitions from parallel to perpendicular

\[ \log_{10} \left( \frac{N_{H_2}}{\text{cm}^{-2}} \right) \]

\[ N_{H_2,\text{tr}} / \text{cm}^{-2} = 10^{21.7} \]
Transition Column Density

Where the column density transitions from parallel to perpendicular

What does this transition tell us?

\[
\log_{10} \left( \frac{N_{H_2}}{\text{cm}^{-2}} \right) = \log_{10} \left( \frac{N_{H_2, tr}}{\text{cm}^{-2}} \right) = 10^{21.7}
\]
Zeeman Measurements of Field Strength

Crutcher et al. (2010) scaling transition volume/number density

When the magnetic field can no longer support against gravitational collapse

Figure 1 — Crutcher et al. (2010)
Magnetic field can no longer support against gravitational collapse

Crutcher et al. (2010)

Scaling Transition Number Density

\( n_{\text{H}_2, \text{tr}} \sim 150 \text{ cm}^{-3} \)
Simulations — Chen et al. (2016)

Scaling transition density is **coincident** with the transition density in 3D HROs.

Figure 4 — Chen et al. (2016)
Magnetic field can no longer support against gravitational collapse

Crutcher et al. (2010)

Scaling Transition Number Density
\[ n_{H_2, tr} \sim 150 \text{ cm}^{-3} \]

Chen et al. (2016)

Alignment (3D) Transition Number Density
Simulations — Chen et al. (2016)

Scaling transition density is coincident with the transition density in 3D HROs.

Behavior can be also be found in 2D HROs

Compute a transition number density value from our HROs for comparison
Magnetic field can no longer support against gravitational collapse

Crutcher et al. (2010)

Scaling Transition Number Density

Chen et al. (2016)

Alignment (2D) Transition Column Density

Chen et al. (2016)

Alignment (3D) Transition Number Density

$n_{\text{H}_2,\text{tr}} \sim 150 \text{ cm}^{-3}$
Magnetic field can no longer support against gravitational collapse

Crutcher et al. (2010)

Scaling Transition Number Density

Chen et al. (2016)

Alignment (2D) Transition Column Density

Chen et al. (2016)

Alignment (3D) Transition Number Density

\[ n_{H_2,\text{tr}} \sim 150 \text{ cm}^{-3} \]

\[ N_{H_2,\text{tr}} \sim 10^{21.7} \text{ cm}^{-2} \]
Magnetic field can no longer support against gravitational collapse

Scaling Transition Number Density

$$n_{H_2, tr} \sim 150 \text{ cm}^{-3}$$

Chen et al. (2016)

Alignment (2D) Transition Column Density

$$N_{H_2, tr} \sim 10^{21.7} \text{ cm}^{-2}$$

Chen et al. (2016)

Alignment (3D) Transition Number Density

$$n_{H_2, tr} \sim 10^{4} \text{ cm}^{-3}$$

Crutcher et al. (2010)
Comparison of Values

\[ n_{H_2,\text{tr}}/\text{cm}^{-3} \]

\[ \sim 150 \]

Crutcher et al. (2010) Zeeman measurements

\[ \sim 10^4 \]

from the HRO analysis of L1688 here
Comparison of Values

\[ n_{\text{H}_2,\text{tr}} / \text{cm}^{-3} \]

\[ \approx 150 \]
Crutcher et al. (2010)
Zeeman measurements

\[ \approx 10^3 \]
Fissel et al. (2019)
Vela C, Molecular Line

\[ \approx 10^4 \]
from the HRO analysis of L1688 here
Comparison of Values

$n_{H_2,\text{tr}}/\text{cm}^{-3}$

Sampling of L1688

- $\sim 150$ (Crutcher et al. (2010) Zeeman measurements)
- $\sim 10^3$ (Fissel et al. (2019) Vela C, Molecular Line)
- $\sim 10^4$ (from the HRO analysis of L1688 here)
Comparison of Values

\[ n_{\text{H}_2,\text{tr}} / \text{cm}^{-3} \]

Sampling of L1688

Particular configuration of simulations

\[ \sim 150 \]
Crutcher et al. (2010) Zeeman measurements

\[ \sim 10^3 \]
Fissel et al. (2019) Vela C, Molecular Line

\[ \sim 10^4 \]
from the HRO analysis of L1688 here
Comparison of Values

\[ n_{H_2, tr} / \text{cm}^{-3} \]

Sampling of L1688

- \( \sim 150 \)  
  Crutcher et al. (2010)  
  Zeeman measurements

Particular configuration of simulations

- \( \sim 10^3 \)  
  Fissel et al. (2019)  
  Vela C, Molecular Line

Viewing angles for the simulation

- \( \sim 10^4 \)  
  from the HRO analysis of L1688 here
Comparison of Values

$n_{H_2, \text{tr}} / \text{cm}^{-3}$

- Sampling of L1688: $\sim 560$ (Jiang et al. (2020) Zeeman measurements)
- Particular configuration of simulations: $\sim 10^3$ (Fissel et al. (2019) Vela C, Molecular Line)
- Viewing angles for the simulation: $\sim 10^4$ from the HRO analysis of L1688 here
Physical Properties

Equipartition of energy at this point

\[ E_K = E_B \]

Figure 5 — Chen et al. (2016)
Physical Properties

Equipartition of energy at this point

\[ E_K = E_B \]

\[ \frac{\rho v^2}{2} = \frac{B^2}{8\pi} \]

Figure 5 — Chen et al. (2016)
Physical Properties

Equipartition of energy at this point

\[ E_K = E_B \]

\[ \frac{\rho v^2}{2} = \frac{B^2}{8\pi} \]

\[ n_{H_2, tr} \sim 10^4 \text{ cm}^{-3} \]

\[ v = 0.5 \text{ km/s} \]

\[ B \sim 30 \mu\text{G} \]

Friesen et al. 2017
Parallel to perpendicular trend seen in Planck Int. Results XXXV appears to continue for L1688

Demonstration of using relative orientation to obtain magnetic field properties

Calculation of transition density is higher than that suggested by previous work

Sampling uncertainty needs to considered and can be improved with more SOFIA observations
TolTEC
Large Millimeter Telescope

1.1 mm
1.4 mm
2.1 mm

5” fwhm @ 1.1 mm
extra slides, extra sides
Ophiuchus

One of the closest star-forming region (~137 pc)

Lots and lots of protostars (e.g., Sadavoy et al. 2019)

Focus on L1688 as that is the region that we have available HAWC+ data

Figure 1 — Ladjelate et al. (2020)
HROs by Subregions of L1688

Right Ascension (J2000)

Declination (J2000)

0.5 parsec

$\log_{10} \deg$ N H$^2$ cm$^{-2}$

$\pm 00^0 00^0 00^0$

$\pm 20^0 00^0 00^0$

$\pm 40^0 00^0 00^0$

$\pm 24^0 00^0 00^0$

$\pm 26^0 00^0 00^0$

$\pm 28^0 00^0 00^0$

$\pm 30^0 00^0 00^0$

}$^\circ$

$\pm 00^0 00^0 00^0$

$\pm 02^0 00^0 00^0$

$\pm 04^0 00^0 00^0$

$\pm 06^0 00^0 00^0$

$\pm 08^0 00^0 00^0$

$\pm 10^0 00^0 00^0$

$\pm 12^0 00^0 00^0$

$\pm 14^0 00^0 00^0$

$\pm 16^0 00^0 00^0$

$\pm 18^0 00^0 00^0$
HROs by Subregions of L1688

[Image of HRO maps for ρ Oph A and ρ Oph E with color bars indicating intensity levels and vectors showing directionality.]

[Graph showing logarithmic column density (log₁₀(N_H₂/cm⁻²)) against right ascension (J2000) with markers indicating preferential parallel and perpendicular directions for each subregion.]
HROs by Subregions of L1688

HRO parameter

preferentially parallel

preferentially perpendicular

\[ \log_{10} \left( \frac{N_{\text{H}_2}}{\text{cm}^{-2}} \right) \]

column density

Right Ascension (J2000)

Declination (J2000)

\[ \pm 0.000 \]

0.5 parsec

\[ \pm 0.000 \]

\[ \pm 0.000 \]
Simulations — Chen et al. (2016)

Colliding flow simulations
Chen & Ostriker (2015)

Isothermal

Initial magnetic field at an oblique angle

Three different inflow Mach numbers

Figure 2 — Chen & Ostriker (2014)