The Role of B-Fields in Star Formation

Thushara G.S. Pillai
Dense ISM Magnetized on all scales

Planck 353 GHz, Soler et al. 2020

~50 pc
Dense ISM Magnetized on all scales

SOFIA HAWC+, Chuss et al. 2019
Dense ISM Magnetized on all scales

SOFIA HAWC+, Chuss et al. 2019
Dense ISM Magnetized on all scales

ALMA 1mm, Cortes et al. 2021
Tools & Techniques

near-IR extinction (diffuse gas)

λ

far-IR emission (envelope and cores)

sub-mm emission (dense gas)
Dust grains in molecular clouds become aligned with their major axes preferentially oriented perpendicular to the magnetic field most likely through radiative torques (Lazarian 2007, Andersson, Lazarian, Vaillancourt ARAA 2015)

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Method</th>
<th>Facility</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2 µm</td>
<td>extincted starlight</td>
<td>MIMIR/Perkins IAGPOL/PdD SIRPOL/IRSF</td>
<td>Pencil beam</td>
</tr>
<tr>
<td>217 µm</td>
<td>dust continuum</td>
<td>SOFIA/HAWC+</td>
<td>19”</td>
</tr>
<tr>
<td>870 µm</td>
<td>dust continuum</td>
<td>APEX, JCMT, CSO</td>
<td>10-18”</td>
</tr>
<tr>
<td>1mm/870 µm</td>
<td>dust continuum</td>
<td>SMA, ALMA</td>
<td>&lt;2”</td>
</tr>
</tbody>
</table>

Pattle & Fissel 2019 for an observation overview
Recipe for Star Formation

Gravity vs. Magnetic Field:

$$\mu = \frac{(M/\phi_B)}{(M/\phi_B)_{cr}}$$

mass-to-flux ratio

$$\mu > 1 \Rightarrow \text{gravity dominates}$$

"Turbulence" vs. Magnetic Field:

$$M_A = 3^{1/2} \frac{\sigma_V}{\sigma_A}$$

Alfven Mach number

$$= (P_{\text{gas}}/P_B)^{1/2}$$

$$M_A > 1 \Rightarrow \text{turbulence dominates}$$
Analysis of Polarized Dust Emission

Chandrasekhar-Fermi formula:

\[ \sigma_\phi \propto \frac{\rho^{1/2} \sigma_v}{B_{pos}} \]

Straightness of field lines

Kinetic Energy

Magnetic Energy

Weak Field

Strong Field

Federrath. 2011

Nakamura & Li 2008
Giant Molecular Clouds
“mean relative orientation between $N_H$ and $B_{\perp}$ toward these regions increases progressively from 0°, where the $N_H$ structures lie mostly parallel to $B_{\perp}$, with increasing $N_H$, in many cases reaching 90°, where the $N_H$ structures lie mostly perpendicular to $B_{\perp}$”
Relation to Gas Volume Density

transition density of $10^3$ cm$^{-3}$

field parallel to elongation

field perpendicular to elongation

Fissel et al. 2019. See also Alina et al. 2019 for clump scale analysis.
Zooming into Dense Filaments within GMCs

HAWC+ Band E, Li et al. 2021

POL2, Pattle et al. 2017
Zooming into Dense Filaments within GMCs

Arzoumanian et al. 2021

Pillai et al. 2020

~1.5 pc
Alignment Transition

known transition at low density

new transition at high density

Pillai et al. 2020
Infrared Dark Clouds

more massive molecular clouds, more representative of galactic SF

small angular extent => cannot use Planck

Pillai et al. 2015
general observation: magnetic field oriented perpendicular to filaments

Santos et al. 2016

Soam et al. 2019
Even more Extreme IRDCs: Galactic Bones

Jackson et al. 2010, Goodman et al. 2014
SOFIA HAWC+: FIELDMAP Survey

about a dozen Galactic Bones

Stephens et al. 2022
Dense Cores
Low-Mass Prestellar Cores

Pattle et al. 2021
μ ~ 1

L1544 Core, OH

Ching et al. 2022

Clemens et al. 2016

L1544 Envelope, HI, μ ~ 3.5

Crutcher et al. 2009

+11±2 μG
Maury et al. 2018. See also Girart et al. 2006

Protostellar Cores

structure resembles pinched magnetic field
More complex systems as well

Sadavoy et al. 2019

Hull et al. 2017
High-Mass Cores

results:

- most outflows orthogonal to the parent filament
- Consequence of filament fragmentation?
High-Mass Cores

results:
complex magnetic orientation in a gravity-dominated regime
half of the outflows in the youngest cores aligned with core-scale $B$-field
High-Mass Protostars

Beuther et al. 2020

very complex field geometry on small spatial scales

Sanhueza et al. 2021
Canonical Knowledge about Magnetic Fields

Crutcher (2010, 2012)
Compendium of Dust-Based Measurements

\[ B = 0.31n^{0.57 \pm 0.03} \]

slope of 0.57

=> between prediction for strong and weak field

Liu et al. 2022

Data consistent with neither highly sub-Alfvenic nor super-Alfvenic turbulence
No obvious trend...
...but SFR per unit mass also hard to measure
Connection to Larger scale ISM

Borlaff et al. 2021, HAWC+
Strategy: Pick filaments at different evolution. But different initial conditions

How does the Initial Sub-Alfvenic Field Evolve as Cloud Evolves?
**SIMPLIFI Fact Sheet**

**Status:** Pilot Phase Fall 2021.

**Main driver:** SOFIA HAWC+ 217 micron dust continuum polarimetry at ~18” resolution

**Complementary Polarization data:** NIR polarization (H & K band with the MIMIR and Pico Dos Dias Instrument), ALMA dust continuum polarimetry for a subset

**Spectral Lines:** low J transitions of CO, $^{13}$CO, C$^{18}$O, N2H$^+$, HCO+ etc.

**Targets (full survey):** Representative Gould Belt regions and Distant high-mass filaments

PI: T. Pillai
Summary
Summary

• MHD turbulence pervades large scale molecular cloud structure
• Magnetic field maps start to pinpoint gravity dominated regimes on cloud scales
• Limited data to establish any influence of magnetization on outflows or SFR
• Prestellar cores are magnetically critical to super-critical
• Hourglass field morphology observed towards some protostars
• Picture still unclear for high-mass stars inc. initial conditions
• A golden era for magnetic field studies in dense ISM with new instruments. Multi-wavelength and multi-scale polarimetry enabled by HAWC+/ALMA will play a major role in the near future.