The Importance of the Magnetic Field from an SMA-CSO-Combined Sample of Star-Forming Regions

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with
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Magnetic Fields in the Universe V, Cargèse; October 7, 2015
Magnetic Field Observational Techniques

* Zeeman splitting:
  needs strong enough line emission,
  can get field strength, typically
  isolated and local (e.g., Crutcher 2012,
  Crutcher+ 2009)

* synchrotron radiation:
  needs relativistic electrons,
  typically not observed (but: HH80–81
  jet, Carrasco-Gonzalez+ 2010)

* absorption of background
  star light by dust
  (polarization in optical / NIR)
  only morphology, no field strength

* thermal dust emission
  (polarization in mm / submm bands)
  only morphology, no field strength

(Chapman et al. 2011)

main difficulty: weak signal, ~ few % of Stokes I
Dust Polarization Mechanism

- Molecular cloud
- CO
- CS
- H$_2$
dust

$\text{n}_{H_2} \sim 10^{4-7} \text{ (cm}^{-3})$
$T \sim 10 \text{ (K)}$

- Individual dust particle: dipole
- In submm: linear polarization from thermal dust emission
- Coherent alignment mechanism: B field is one possibility
- Mechanism provides only projected field orientation/morphology
- Need something more to derive field strength

(e.g. Hildebrand 1988, Lazarian 2007...)
to start with:
Larger Scale Interstellar Medium by Planck

Taurus molecular cloud complex; dust continuum at 350 GHz 15’ resolution

(Planck XXXII, 2014; poster by Andrea Bracco)
Planck: Interstellar Medium

- Magnetic field vs structure:
  - Field tends to be aligned with ridges in diffuse ISM.
  - Alignment progressively changes as column density increases.

- Interpretation:
  Magnetic field is guiding material, possibly significant level of turbulence organizing material parallel to magnetic field.

- Question:
  How does the role of the magnetic field evolve towards smaller scales?

- Utilize dust polarization observations on smaller scales with the SMA, CSO, JCMT, (ALMA).

\( \xi = 1 \): Field aligned with ridges
\( \xi = -1 \): Field orthogonal to ridges

Filamentary molecular cloud

(Planck XXXII, 2014)
Magnetic Field Observations on Smaller Scales
among the currently highest-resolution polarization observations, ~ 0.7"
- clearly resolved, shaped and pinched field structures:
  *often field closely aligned with gradients*
Key Observable: angle $\delta$

motivation:
clear correlation in orientations between intensity gradient and field orientations!

(W51 e2 (SMA, $\Theta \sim 0.7''$))

(Koch, Tang & Ho, 2012a,b)
Increasing Sample Size: SMA Polarization Legacy Program and CSO archival data

* about 20 additional sources (new or deeper integration, dedicated SMA legacy program, Zhang + SMA pol legacy team, 2014)

  total: about 30 sources in polarization with the SMA

* high-mass sites with density \( > 10^5 \) cm\(^{-3}\) on scales 0.1 to 0.01 pc, resolutions around 1” - 3”

* additionally: CSO archival data (about 20 sources), covering scales of \(~ 1\) pc

* total sample: 50 sources (low- and high-mass star forming regions)
B \perp \text{major axis}

\begin{itemize}
  \item Dominating in Planck data
\end{itemize}

(Zhang+ 2014)
SMA Polarization Legacy Program + CSO Archival data: Magnetic Field vs Dust Continuum Structure

- **prevailing field orientation**: roughly parallel to source minor axis (not bimodal)

- **opposite to Planck result**: field tends to be aligned with ridges in diffuse ISM
- intermediate scales: expect results from BLASTpol (poster by Laura Fissel)
- magnetic field very likely plays different roles as a function of scales

(Koch + SMA pol legacy, 2014)
What is $\delta$?

(Koch, Tang & Ho, 2013)

- $\delta$ measures alignment
- fraction of field tension force oriented along gradient

project $n_B$ into orthonormal system (normal, tangential to contour)

\[
\rho \left( \frac{\partial}{\partial t} + v \cdot \nabla \right) v = -\nabla P - \rho \nabla \phi + \sin |\delta| \frac{1}{4\pi} \frac{1}{R} B^2 n_\rho + \sin |\alpha| \frac{1}{4\pi} \frac{1}{R} B^2 t_\rho
\]
What can we learn from $\delta$?

Magnetic Field Strength Map

$$B = \sqrt{\frac{\sin \psi}{\sin \left(\frac{\pi}{2} - |\delta|\right)}} (\nabla P + \rho \nabla \phi) 4\pi R$$

Field-to-Gravity Force Ratio $\Sigma_B$

$$\Sigma_B \equiv \frac{\sin \psi}{\sin \left(\frac{\pi}{2} - |\delta|\right)} = \frac{F_B}{|F_G + F_P|}$$

(Koch, Tang & Ho, 2012a,b; 2013)
δ across a Sample of 50 sources (SMA+CSO): $\Sigma_B$

- average $<|\delta|>$ is systematically different across sample
- $<|\delta|>$ is typically small for sources with magnetic field parallel to source minor axis, $<|\delta|>$ grows for sources with field parallel to major axis
- $<\Sigma_B>$ grows systematically with $<|\delta|>$ with a transition across 1
$\delta$ across a Sample of 50 sources (SMA+CSO): mass-to-flux ratio

(Koch+ SMA pol legacy, 2014)
Conclusions

- **observations:**
  * $\delta$ is a key observable, discriminating between different types of source - magnetic field configurations;
    seen in SMA, CSO, JCMT (and BIMA / CARMA) data
  * prevailing field orientation is parallel to source minor axes;
    Planck observations of larger-scale ISM: opposite trend
  * $\delta$ is a tracer of the role of the magnetic field
    (sub-, supercritical; star formation efficiency)
  * sample of 50 sources: $\delta$ and $\Sigma_B$ show clear correlation;
    i.e., the larger $\delta$, the more the field dominates gravity

- **methodology:**

  basic idea: observed morphology reflects geometrical imprint of combined forces. This leads to:
  * force ratio $\Sigma_B$ (depends on angles only)
  * local magnetic field strength $B$