Magnetic Fields in Molecular Clouds

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SMA

ALMA

CSO/SHARP

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outline

- motivation: B-field, why and how?
- filamentary infrared dark cloud G34.43
- high-mass star-forming region: W51 e2, e8, North
- beyond imaging: novel analysis techniques and statistics
- indirect constraint on B-field: specific angular momentum profile in young stellar objects
why should you care about magnetic fields in star-forming regions?

* field strength is measured (e.g. Zeeman splitting), 0.1 mG to a few mG, can be dominating, comparable or at least non-negligible as compared to thermal pressure, gravity, centrifugal force

* magnetic field is fundamental physical constituent, i.e., Lorentz force, addressing basic concepts of flux-freezing, ambipolar diffusion

* with ALMA’s sensitivity, fidelity and absolute calibration: need to expect to see magnetic field influence (“indirect” measurements) e.g. different dynamics, different velocities and time scales
context and key questions around B-field

- how does the B-field affect dynamics of star formation?
- B-field versus gravity, B-field versus turbulence?
- can the B-field influence star-formation efficiency?
- how are B-field and gas coupled?
- is magnetic braking in protostellar disks happening?
- how far can we constrain dust properties with polarization?
Magnetic Field Observational Techniques

- **Zeeman splitting:** needs strong enough line emission, can get field strength, typically isolated and local

- **synchrotron radiation:** needs relativistic electrons, typically not observed

- **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

*main difficulty: weak signal, ~ few % of Stokes I*

(Chapman et al. 2011)
Dust Polarization Mechanism

- 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

$n_{H_2} \sim 10^{4-7} \text{ (cm}^{-3}\text{)}$

$T \sim 10 \text{ (K)}$

paramagnetic, elongated, rotating Radiative Alignment Torque (RAT) theory

(e.g. Hildebrand 1988, Lazarian 2000, Hoang & Lazarian 2016, Andersson+2015)
filaments are ubiquitous (Herschel)
- being established as an essential building block in SF process
- how are they formed in a first place? how are the denser structures within filaments formed?
what is the role of the B-field in this process?

- example observation/analysis: G34.43
IRDC G34.43

- distance: 3.7 kpc, elongated length ~ 8 pc
- mass: 1200 $M_\odot$ (mm1), 1300 $M_\odot$ (mm2), 300 $M_\odot$ (mm3)
- overall, very small viral parameter ($\alpha \sim 0.2$), system gravitationally bound, but SF efficiency only ~ 7%.
  additional support from B-field?
- observed with the CSO/SHARP (350$\mu$m, resolution 10")
- polarization percentage 0.4 - 10%
- B-field clearly organized perpendicular to longer axis around mm1/mm2; more aligned with longer axis on mm3, small dispersion
- add line kinematics: $N_2H^+$ (1-0) from IRAM-30m ($\theta \sim 28\arcsec$), clear large-scale gradient

Peretto+2017  Tang+2018  Rathborne+2006
B-field, velocity gradient, turbulence & gravity

which component is dominant? negligible? - benchmark analysis

B vs v: small differences and spatially not random, but organized
B vs G: spatially not random, but organized

(Tang+2018)
How Important is the B-field in G34.43?

which component is dominant? negligible? - benchmark analysis

different local interplay between B-field, turbulence, and gravity on core scale

⇒ consequence for fragmentation towards next smaller scale?
Fragmentation in G34.43

- **clustered fragmentation**
  - $G > T \geq B$
  - largest dispersion in $B$
  - weakest $B$
  - smallest mass

- **no fragmentation**
  - systematic dispersion in $B$ (drag)
  - medium $B$
  - larger mass

- **aligned fragmentation**
  - $B > G > T$
  - smallest dispersion in $B$
  - strongest $B$
  - larger mass

Tang+2018
SMA: Zhang+14; Chen+in prep.
CARMA: Hull+14
Higher-Resolution B-field Measurements

- W51 high-mass SF site at $d \sim 5.4$ kpc
- several UCHII regions and infalling signatures detected
- elongated structure, with B-field mostly perpendicular (BIMA, $\theta \sim 3''$, Lai+2001)
- SMA observations: resolved B-field in cores with $\theta \sim 0.7''$ (Tang+2009)
W51 e2/e8 with BIMA and SMA

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- elongated structure, with B-field mostly perpendicular (BIMA, $\theta \sim 3''$, Lai+2001)
- SMA observations: resolved B-field in cores with $\theta \sim 0.7''$ (Tang+2009)
- clearly varying B-field structure as a function of scale
- channeling from North and South towards mid-plane
- denser cores in mid-plane along east-west direction

(Tang+2013)
First ALMA Polarization Observations towards W51

ALMA cycle 2/3 (230 GHz (B6), \( \theta \sim 0.26'' \sim 5 \) mpc; Koch+2018)
pol. percentages \( \sim 0.1 - 10\% \); sensitivities 1mJy/b in Stokes I, 0.1 mJy/b in Q,U
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- new sub-structures:
  - cometary-shaped B-field in e2-NW, e8-S, symmetric convergence zones (yellow)
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Gravity vs Magnetic Field

- How important is the magnetic field in e2-E, e2-W and e2-NW?
- In which cores can it still slow down gravitational infall?
- Where is the field already overwhelmed by gravity, and might there be even local differences within the same core?

- compare local direction of B-field ($n_B$) with direction of local gravity ($g$)
- adopt ideal MHD force equation

\[
C = \frac{1}{2} \frac{1}{4\pi R} B^2 \sin \omega
\]

\[
\rho \left( \frac{\partial}{\partial t} + v \cdot \nabla \right) v = -\nabla P - \rho \nabla \phi + \frac{1}{4\pi R} B^2 n_B
\]

\[
\rho \left( \frac{\partial}{\partial t} + v \cdot \nabla \right) v = -\nabla P - \rho |\nabla \phi| g + \frac{1}{4\pi R} B^2 \sin \omega g + \frac{1}{4\pi R} B^2 \cos \omega n_g
\]

\(\sin \omega\) quantifies B-field effectiveness to oppose gravity (Koch+2018)
Convergence Zones, Magnetic Channelling and Star Formation Efficiency

- $\sin\omega$, in the range between 0 and 1, measures how effectively the B-field can oppose gravity.
  - $\sin\omega \approx 0$: gravity/collapse proceeds freely
  - $\sin\omega \approx 1$: B-field works maximally against gravity, holding back material

- W51 e2: network of narrow magnetic channels (black) with $\sin\omega \approx 0$

- Note: many channels coincide with convergence zones

- Consequence for star formation efficiency?
  - Assume ~ 2" diameter sphere, ~0.15" channel width, ~10 channels
  - 1 channel ~ 0.4% of entire mass (volume); if only mass within channels takes part in star-formation process: star-formation efficiency reduced to ~ 4% for W51 e2
Convergence Zones, Magnetic Channelling and Star Formation Efficiency

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North

Consequence for star formation efficiency?
**Key Observable:** angle $\delta$

**motivation:**

*clear correlation in orientations between intensity gradient and field orientations!*

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

Koch, Tang & Ho, 2012
What can we learn from $\delta$?

Magnetic Field Strength Map

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

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)
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 around 1 pc

* total sample: 50 sources (low- and high-mass star forming regions)
Beyond Imaging: Statistics
50-source sample SMA / CSO observations

- field morphology is organized
  (not necessarily uniform, but clearly not random)

- field morphologies are systematic
  key observable: angle $\delta$ between emission gradient and magnetic field
δ across a Sample of 50 sources (SMA+CSO)

- average $<|δ|>$ is systematically different across sample
- $<|δ|>$ is typically small for sources with magnetic field parallel to source minor axis, $<|δ|>$ grows for sources with field parallel to major axis
- $<Σ_B>$ grows systematically with $<|δ|>$ with a transition across 1
where are we standing? one step back:
Larger Scale Interstellar Medium by Planck

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

(Planck XXXII, 2014)
Planck: Interstellar Medium

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

- **prevailing field orientation**: roughly parallel to source minor axis

- **connecting to Planck result**: (Planck XXXII, 2014/2016)
  field tends to be aligned with diffuse ridges in diffuse ISM, but progressively changes as column density increases

- magnetic field very likely plays different roles as a function of scales and location

50 sources,
~ 4000 independent measurements
density regime: $10^5$ cm$^{-3}$ or higher

(Koch + SMA pol legacy, 2014)
Numerical Work

- simulating large-scale filamentary structures (Planck, BLASTPol)

- “Histogram of Relative Orientations” between magnetic field and density structures (equivalent to angle $\delta$)

- histograms carry information on magnetization, age, and column density

(Soler, Hennebelle+2013)
Conclusions

- **filament:**
  * organized B-field, mostly perpendicular to filament,
  B-field channelling material, “G vs B vs T” locally different
  
  * relative significance of G,B, and T hints different fragmentation scenarios

- **ALMA:**
  * detailed magnetic field morphologies reveal dynamical picture:
    convergence zones, magnetic channelling, cometary-shaped satellites
  
  * sin ω quantifies B-field effectiveness to oppose gravity

- **protostellar source:**
  * tracing spec. ang. mom. profile can constrain magnetic braking

- **analysis techniques:** δ is a key observable, leading to local field strength measurement and local force ratio Σ_B

- **sample:**
  * δ and Σ_B discriminate between different types of magnetic-field configurations (possibly different evolutionary stages)
  
  * sample of 50 sources: δ and Σ_B show clear correlation;
    i.e., the larger δ, the more the field dominates gravity
additional slides
A Note on Polarized Emission and Polarization Percentages

- complicated but organized structure in polarized emission $I_p$

- some correlation with local B-field dispersion $S$ (also seen on larger scales in Fissel+2016; Planck XIX, XX, 2015)

- typical anti-correlation between polarization percentage $p$ and total intensity Stokes $I$, slope $\sim -1$, but with very large scatter

\[ p = \frac{I_p}{I} \]

\[ I_p \]
A Note on Polarized Emission and Polarization Percentages

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What is $\delta$?

(Koch, Tang & Ho, 2012a,b; 2013)

- $\delta$ measures alignment
- fraction of field tension force oriented along gradient
- $\delta$ quantifies local magnetic field-to-gravity force ratio $\Sigma_B$

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

$$\rho \left( \frac{\partial}{\partial t} + v \cdot \nabla \right) v = -\nabla P - \rho \nabla \phi + \frac{1}{4\pi} \frac{1}{R} B^2 n_B$$

$$\rho \left( \frac{\partial}{\partial t} + v \cdot \nabla \right) v = -\nabla P - \rho \nabla \phi + \sin |\delta| \frac{1}{4\pi} \frac{1}{R} B^2 \mathbf{n}_\rho + \sin |\alpha| \frac{1}{4\pi} \frac{1}{R} B^2 \mathbf{t}_\rho$$
New Method for Local Magnetic Field Strength

(1) assumption:

intensity gradient is a measure for resulting direction of motion

(2) close 'force triangle':

\[ B = \sqrt{\frac{\sin \psi}{\sin \alpha} (\nabla P + \nabla (\rho \Phi)) 4\pi R} \]

MHD force equation:

\[ \rho \nu \frac{\partial \psi}{\partial s_y} e_{s_y} + \rho \nu^2 \frac{\partial e_{s_r}}{\partial s_y} = -\frac{\partial P}{\partial s_y} e_{s_z} - \frac{\partial}{\partial s_{\psi}} (\rho \Phi) e_{s_{\psi}} + \frac{1}{4\pi} B^2 \frac{1}{R} \mathbf{n} \]

associated with intensity gradient; result of all the acting forces leading to observed gas distribution

local gravity direction; derived from summing all the mass (emission) distribution

field tension force; orthogonal to detected field orientation
δ across a Sample of 50 sources (SMA+CSO): mass-to-flux ratio

(Koch+ SMA pol legacy, 2014)
W51 North form large to small scales

(Tang+2013)
Specific Angular Momentum Profile

indirect way:  
- can precisely measure / model profile with ALMA
- if angular momentum removed from envelope to inner disk, observable in profile
- associate removal with magnetic braking, get B strength

B335

Resolutions from 33” to 0.3”
Structures from 0.1 pc to 40 AU

No disk > 10 AU

Yen+2015
Specific Angular Momentum Profile

Saito et al. 1999; Kurono et al. 2013

Yen+2015
Specific Angular Momentum Profile

Magnetic braking?

Alternative: different infalling radius, younger age

\[ V_{in} \frac{\Delta j}{\Delta r} = \frac{rB_zB_\phi}{2\pi\Sigma} \]

200 micro Gauss