Magnetic fields and massive star formation

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Role of Magnetic Field in Star Formation

- Cloud scale: formation/support – magnetic or turbulent?
- Clump Scale: What controls clump fragmentation and core formation? Does massie SF proceed in equilibrium?
- Core – disk Scale: Magnetic braking - remove angular momentum?

NGC1333 IRAS4A
Girart et al. 2006

B field direction
870 µm Cont.

Chapman et al. 2010

See review by McKee & Ostriker 2007 Crutcher 2012
Techniques to Measure B-fields

- Zeeman Splitting: $B_{\text{los}}$, limited by sensitivity unless for masers.
- Linear polarization caused by aligned aspherical dust grains in presence of $B$ fields (Emission: $\text{Pol} \perp B$; Absorption: $\text{Pol} \parallel B$): Measure morphology only, infer $B_{\text{pos}}$
- Goldreich & Kylafis effect

See Review by Crutcher 2012, Lazarian 2007
Magnetic field morphology from dust polarization

Diagnostic tools:
Comparing magnetic field orientation (Bpos) at different spatial scales
Comparing Bpos orientation with respect to cloud morphology
Using dispersion of Bpos orientation $\rightarrow B$
Magneto hydrodynamic simulation with turbulence: Sheets

- Gas collapse along field lines to form dense filaments $\perp B$
- Diffuse and lower density gas $\parallel B$

$\beta = \frac{P_{th}}{P_B} = 1/24$, Strong $B$ field

Nakamura & Li (2008)
See also Nagai et al. 1998; Soler et al. 2013; van Loo et al. 2014

Apri 6-9, 2016
NGC 6334: Magnetic fields from GMC to cores

- Magnetic field orientation maintained from 100pc to 0.1 pc

Li et al. 2015
See also Zhang et al. 2014

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Massive Filaments in G14.2

Busquet, Zhang et al. 2012

- Cloud size ~ 8 pc
- 74 clumps
- Masses: 11-1000 M☉
- Clump sizes: 0.2-1.2 pc

VLA NH₃ on Spitzer 8 μm
Massive Filaments in G14.2

\[ \alpha = \frac{M_{\text{vir}}}{M} = \frac{5\sigma^2 R}{GM} \]

What about support from B fields?

B = 0.3-0.5 mG

\[ \alpha = 2 \]

Santos+ 2016

See also Pillai+ 2015

B field from IR

Ohashi+ 2016, in prep

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Cores contain many Jeans mass (Case study G28.34)

For spatially resolved cores (res < L_J)

\[
M_{\text{core}}/M_J > 10
\]

n(H₂)=7x10⁴ cm⁻³, T=15K

M_J (thermal) = 2 Msun

L_J = 0.1 pc

\[
M_J = \frac{\pi}{6} \left( \frac{\pi C_s^2}{G} \right)^{3/2} \rho_o^{-1/2}
\]

σv=0.7 km/s

M_{\text{turb, } J} \sim 30 \text{ Msun}

L_{\text{turb, } J} \sim 0.3 \text{ pc}

Turbulence (and B field) supported fragmentation?

Zhang, Wang, Pillai, Rathborne 2009

Is cluster forming region G28 in equilibrium

\[ \alpha = \frac{M_{\text{vir}}}{M} = \frac{5\sigma^2 R}{GM} \]

Zhang et al. 2009; 2015; Zhang et al. 2015
Many Cores are sub-virial: \( M_{\text{vir}}/M < 1 \)

Lu et al. 2014

distribution of the virial parameter

See also Pillai+ 2011, Kauffmann+ 2013
21 massive molecular clumps, largest by (sub)mm interferometer

Subcompact/compact/extended configurations → 1-3”

Goal: To obtain data for a large sample of massive molecular clumps to investigate the role of magnetic fields in fragmentation of massive molecular clumps and formation of cores through imaging of dust/CO polarization, and kinematics of molecular gas.

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Summary paper:

Detailed analysis:
- Li, H., et al. 2015, Nature, 520, 518
G240: Dust Polarization and Outflow

$B = 1.2 \text{ mG}, \beta = 0.4, M/\text{Flux} = 1.1$

G240.31 ($10^{4.7} \text{ L}_\odot$): Qiu et al. 2009, 2014


Single Dish: Matthews et al. 2009; Dotson et al. 2010
Polarization Maps
DR21 Filament in Cygnus X

Girart et al. 2013
Kirby et al. 2009
Hennemann et al. 2012

0.8 mm continuum and B field direction

CSO

SMA: DR 21(OH)

Hennemann et al. 2012

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B field in core scales versus B field in clump

- Two groups of cores: One group with $B_{\text{core}} \parallel B_{\text{clump}}$, Other group $B_{\text{core}} \perp B_{\text{clump}}$.
- $>60\%$ of small scale B follow direction of $B_{\text{clump}}$.
- The bi-modal distribution suggests that B fields are dynamically important during the collapse of pc-scale clumps and the formation of 0.1pc dense cores.

**Simulation:** B-fields aligned within a 35° cone

**Simulation:** B-fields aligned within a 80-90°

Zhang et al. 2014

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Why there is a peak at 90d?

- From the lower density gas dragged along the large scale magnetic field lines? (sample is too small to tell).

- Angular momentum (rotation) at core scales drags the field, rendering it perpendicular to the large scale field? (There is a hint in the data, and should be investigated further)

- Sample studied is still small, the peak at 90d might be caused by few objects.
B field in cores versus outflows

- Small # of statistics, but there appears to be no preferred alignment ➔ Angular momentum dominates B field at $10^3$ AU scale? Or gas and B decoupled in dense regions?

![Graph showing the distribution of $|\theta_{\text{outflow}} - \theta_{\text{SMA}}(B)|$ (Degree)]
Conclusions

- Recent polarization data of statistically significant samples found magnetic fields are correlated in scales from clumps (1pc) to cores (0.01-0.1pc).
- Statistical analysis finds 1 - 10 mG in clumps and cores.
- These findings indicate magnetic fields are dynamically important at these scales and play a dynamically important role in massive star formation.
- Magnetic fields in dense cores do not correlate with outflow axis, suggesting that in (peudo)disk scales, angular momentum dominates over magnetic fields.