Magnetic Fields in Molecular Clouds

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Question 1: How strong is the mean magnetic field of GMCs?
The formation of GMCs from large-scale compressions:
– General argument about trans-Alfvénic MHD turbulence
– Large-scale (~200pc) multiphase turbulence simulations

Question 2: How strong is the rms magnetic field of GMCs?
Magnetic field amplification in supersonic MHD turbulence:
– Small-scale (~5-20pc) isothermal turbulence simulations

Question 3: Are weak fields in GMCs consistent with observations?
Comparison of simulations with Zeeman measurements:
– Energy ratios
– Core versus envelope
Question 1:

How strong is the **mean** magnetic field of GMCs?
Two different views on the magnetic field strength in clouds

1) The “traditional” view of molecular clouds

**Strong mean magnetic field:** Molecular clouds are magnetically supported

\[ E_G \sim E_K \sim E_M \gg E_{TH} \quad \rightarrow \quad \text{Star formation is controlled by ambipolar drift} \]

(see review by Shu, Adams & Lizano 1987)

2) The super-Alfvénic model of molecular clouds

*Padoan and Nordlund (1997-1999): The mean magnetic field is weaker*

\[ E_G \sim E_K > E_M > E_{TH} \quad \rightarrow \quad \text{Super-Alfvénic turbulence:} \]

- Molecular clouds are not magnetically supported
- The $B$ field detected in dense cores is much larger than the mean $B$ field
- **Prestellar cores are formed by turbulent shocks, not by ambipolar drift**
Why are GMCs born super-Alfvénic?

GMCs are formed by large-scale compressions in the warm ISM (SN remnants).

– Before the compression, the turbulence is trans-Alfvénic, or mildly super-Alfvénic.

– After the compression: \( \rho_{\text{cold}} \sim 100 \rho_{\text{warm}} \rightarrow E_{K,\text{cold}} = \rho_{\text{cold}} u^2 / 2 \sim 100 E_{K,\text{warm}} \)

The magnetic energy per unit volume initially does not change much

→ the turbulence becomes highly super-Alfvénic and supersonic.

→ \( B \) is locally stretched and compressed so \( <B^2> \) grows, with \( <B> \sim \text{const.} \)

Compressed warm gas: \( E_K \sim E_M \sim E_{\text{TH}} \)

Cold turbulent gas: \( E_K > E_M > E_{\text{TH}} \)
Large-scale multiphase MHD turbulence (PPML – 512³)

Previous works with SN driving (Korpi et al. 1999; Mac Low et al. 2005; De Avillez and Breitschwerdt 2005, 2007; Joung and Mac Low 2006, 2009) have stressed the important role of dynamic pressure:
– Large gas mass fraction out of thermal equilibrium
– Densities and temperatures of GMCs are reached without gravity
– GMCs could be transient (though their cold gas may be longer-lived)
– Effective driving scale ~ 75 pc
– $\delta B/B_0 \sim 1$, not very large

Kritsuk et al. 2010: Idealized turbulent box:
– $L = 200$ pc, random solenoidal forcing $1 < k < 2$, no SN, no gravity
– Periodic domain, $512^3$ zones, $L = 200$ pc $\rightarrow \Delta x = 0.39$ pc
– $M_s \approx 4$, $Ma \approx 2$ (using mean gas pressure and $B_0$)
– $<n> = 5$ cm$^{-3}$, $n_{\text{max}} \approx 5,000$ cm$^{-3}$, $T_{\text{min}} = 18$ K
– Analytical cooling and heating rate approximations from Wolfire et al. 2003

Result: GMCs have $<B> \sim B_0$ (large-scale mean magnetic field), even if they are $\sim 100$ times denser than the mean.
Cold clouds: \( \langle B_{\text{MC}} \rangle \approx 2 B_0 \), \( \langle B_{\text{GMC}} \rangle \approx B_0 \)

→ Clouds are born with a weak mean magnetic field
→ Almost no \( B \) compression going from warm gas to cold clouds!
As a result of the weak mean magnetic field, GMCs are super-Alfvénic with respect to their own $<B>$.

Only smaller clouds can be in equipartition, or sub-Alfvénic (but notice that all clouds were selected with the same density threshold, $\sim 100 \text{ cm}^{-3}$).

$$<B_{\text{GMC}}> \approx B_0$$  \hspace{1cm}  $$<\mathcal{M}_{\text{A,GMC}}> \approx 5$$
Velocity-size relation: Large clouds have large velocity dispersion, but $\langle B \rangle \sim B_0$ (flat $B-n$ relation), hence they are very super-Alfvénic.
Question 2:

How strong is the $\text{rms}$ magnetic field of GMCs?
Numerical simulations of MHD turbulence (PPML – 1024³)  
(Ustyugov et al. 2009; Kritsuk et al. 2009a,b, 2010)  
– Uniform initial magnetic and density fields  
– Large scale (1 < k < 2), random, solenoidal initial velocity and forcing  
– Forcing for several crossing times → steady state  
– No gravity, no ambipolar drift, isothermal equation of state

\[ \beta_0 = 2 \frac{c_s^2}{v_{A,0}^2} = 2 \left( \frac{M_{A,0}}{M_S} \right)^2 \]

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All these models are super-Alfvénic with respect to the mean magnetic field (lower mean magnetic field than in the “standard” model).

Is \( <B^2> \) amplified to equipartition by a turbulent dynamo?
Time evolution of magnetic energy

Rapid saturation of $E_m$ to a level below equipartition for $M_{A,0}=10$ and 30

→ The turbulent dynamo is inefficient in supersonic turbulence.

Haugen et al. 2004: At $Pr_M\sim 1$ and $M_S\sim 2.5$ the critical magnetic Reynolds number for dynamo action is $Re_{M,cr}=80$, and depends weakly on $M_S$. But they find some evidence of growth rate decreasing with increasing $M_S$. 
The “GMCs” selected from the multiphase runs have $M_{A,0}$ in the range 2 – 9.

According to the isothermal runs, approximately half of these GMCs should reach equipartition with respect to the rms $B$, in $2 - 3$ dynamical times.

Indeed, their $M_{A,rms}$ values are scattered within a factor of two above the saturated values of the $1,000^3$ isothermal runs → Age of transient GMCs in the turbulent flow?
Question 3:

Are weak fields in GMCs consistent with observations?
Synthetic Zeeman Measurements from MHD Simulations

*Lunttila et al. 2009*: Solution of the coupled radiative transfer equations for the four Stokes parameters (1665 and 1667 MHz OH lines)

Very low mean field, \( <B> = 0.34 \mu G \) (but \( <B^2>^{1/2} = 3.05 \mu G \))

1665 MHz OH Integrated Intensity

Core selection in the 1665 MHz OH maps (3' beam) with P-P-V clumpfind algorithm *(Williams et al. 1995)*: Cores correspond to brightness temperature peaks (not so much to projected density structures).
Comparison with Observations \textit{(Troland and Crutcher 2008)}

Using only detections:
\[
\langle \lambda \rangle_{\text{sim}} \approx 2.5 \pm 0.4, \quad \langle \lambda \rangle_{\text{obs}} \approx 2.5 \pm 0.6
\]
\[
\langle \beta_{\text{turb}} \rangle_{\text{sim}} \approx 0.6 \pm 0.4, \quad \langle \beta_{\text{turb}} \rangle_{\text{obs}} \approx 0.9 \pm 0.6
\]

The mass-to-flux ratio and the magnetic-to-kinetic energy ratio in the cores are consistent with the observations, despite the very low mean magnetic field.
Is the mean $B$ in the envelope as strong as inside the dense core?

Strong Mean Field: $E_G \sim E_K \sim E_M$

Cores formed by ambipolar drift

Weak Mean Field: $E_G \sim E_K > E_M$

Cores formed by turbulent shocks
Ratio between mass-to-flux in the core and in the envelope

Prediction of super-Alfvénic turbulence (*Lunttila et al. 2008*):
Large scatter in $R_\mu$, $R_\mu < 1$ for $B > 10 \mu G$

Prediction of ambipolar-drift model of core formation (*Ciolek & Mouschovias 1994*): $R_\mu > 1 \sim 4$

*Crutcher et al. 2008*: $R_\mu = 0.41 \pm 0.2$ (for the core B1)
Conclusions

- Giant Molecular Clouds are super-Alfvénic with respect to their $<B>$.  
- In most GMCs the turbulence may remain super-Alfvénic also with respect to $<B^2>^{1/2}$, unless $\mathcal{M}_{A,0} \leq 3$ and the cloud is older than $\sim 2$ dynamical times. 
- Super-Alfvénic simulations yield magnetic field strength and energy ratios in dense cores consistent with the observed values based on Zeeman measurements.  
- The predicted relative mass-to-flux ratio (core to envelope) is consistent with Zeeman measurements of molecular cores.