The Magnetic Field of GMCs

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Two different views of the magnetic field in MCs:

1. The old view
(Shu et al. 1987)

Strong mean magnetic field: MCs are and magnetically supported

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

2. The Super-Alfvénic model of MCs
(Padoan & Nordlund 1999)

Weak mean magnetic field: MCs are NOT magnetically supported

\[ E_K \geq E_G > E_M > E_{\text{TH}} \quad \rightarrow \quad \text{Prestellar cores from turbulent shocks, not amb. drift} \]
Question 1: How strong is the mean magnetic field of MCs?
- Formation of GMCs from large-scale compression (~energy equipartition)
- Large-scale (200 pc) multi-phase turbulence simulations
- Large-scale (500 pc) SN-driven simulations

Answer 1: MC turbulence is super-Alfvénic

Question 2: How strong is the rms magnetic field of MCs?
- Magnetic field amplification in supersonic MHD turbulence
- Small-scale (5-20 pc) isothermal turbulence simulations
- Large-scale (200-500 pc) multi-phase simulations

Answer 2: Amplification is below equipartition and NOT from a dynamo

Question 3: Is a weak field in MCs consistent with observations?
- Comparison of the simulations with Zeeman measurements
- Observed anisotropy of the velocity field
- Comparison with polarization measurements

Answer 3: Yes, it is consistent
Question 1: How strong is the mean magnetic field of MCs?
GMCs must be born super-Alfvénic
GMCs are formed by large-scale compressions in the warm ISM (SN remnants)

Before the compression approx. equipartition:
Turbulence is trans-Alfvénic, so $B$ cannot be compressed and amplified. The compression must be predominantly along the field.

After the compression:
\[ \rho_{\text{cold}} \sim 100 \rho_{\text{warm}} \quad \rightarrow \quad E_{K,\text{cold}} \sim 100 E_{K,\text{warm}} \]
\[ T_{\text{cold}} \sim T_{\text{warm}} / 100 \quad \rightarrow \quad E_{TH,\text{cold}} \sim E_{TH,\text{warm}} / 100 \]
\[ B_{\text{cold}} \sim B_{\text{warm}} \quad \rightarrow \quad E_{M,\text{cold}} \sim E_{M,\text{warm}} \]
Projected density evolution over ~30 Myr with selfgravity and “real” SNe
Idealized 200-pc volume with PPML (Kritsuk et al. 2010-2017)

- **Physics**: 3D MHD equations, parametrized cooling and heating, random solenoidal force

- **Resolution**: $dx=0.2$ pc ($512^3$ and $1024^3$ uniform grids)

- **Initial conditions**: Uniform $n=5$ cm$^{-3}$, uniform $B=5$ $\mu$G

- **Time evolution**: few dynamical times, without self-gravity
Cold clouds: \(<B_{MC}> \approx 2 B_0\), \(<B_{GMC}> \approx B_0\)

—> Almost no B compression going from warm gas to cold clouds
—> GMCs are born with a weak mean magnetic
GMCs are super-Alfvénic with respect to their mean magnetic field

\[ \langle B_{MC} \rangle \approx 2 \, B_0 \]

\[ \langle M_{A,MC} \rangle \sim 5 \]
Realistic Larson velocity-size relation without self-gravity

It explains why larger clouds are more super-Alfvénic
More realistic 250-pc volume with RAMSES (Padoan et al. 2016-2017):

- **Physics**: 3D MHD equations, parametrized cooling and heating, individual SNe (thermal energy with exponential profile)

- **Resolution**: $dx=0.0076$ pc ($512^3$ root grid + 6 AMR levels), $r_{SN} = 3dx=0.02$ pc, 2.5e8 tracers

- **AMR criteria**: pressure and density *gradients*, density levels ($dx / \lambda_J = \text{const}$)

- **Initial conditions**: Uniform $n=5$ cm$^{-3}$, uniform $B=4.6$ $\mu$G

- **Time evolution**: 45 Myr with random SNe + 32 Myr with self-gravity, SF and **real SNe**

  ~100 M core hours and 1 yr wall-clock time, ~ 7,000 stars and hundreds of MCs (NASA High-End Computing, Pleiades)

- **CAVEATS**: No chemistry (H2 and CO formation), no escape of hot gas.
We simulate a 250 pc \((\text{periodic})\) 2.e6 M\(\odot\) chunk of a spiral arm.

Outer scale \(\lesssim 100\) pc, so going much above 250 pc is an overkill.

First random SNe, \(\sim 6\) SNe/Myr

Then \textbf{real SNe} from resolved stars
We select MCs based on density (in 3D) or antenna temperature (with synthetic CO lines) and compare them with observed clouds from the **Outer Galaxy Survey** *(Heyer et al. 2001)*

and

Similar MC properties, but larger $\Sigma_{cl}$, in the **Galactic Ring Survey** *(Roman-Duval et al. 2010)*
Velocity-Size Relation

From 3D density selection

From CO brightness selection

- The relation is the same before and after gravity
- The slope of the relation is independent of the threshold for MC selection
- Same vertical scatter and slope as in the observations
Magnetic field strength on GMC scale

- GMC turbulence is super-Alfvénic, for any cloud above 1,000 $M_\odot$
- It is super-Alfvénic even with respect to the rms B field
Question 2:

How strong is the \textit{rms} magnetic field of MCs?
Idealized 10-pc region with PPML (Kritsuk et al. 2009-2010)

- **Physics**: 3D MHD equations, ISOTHERMAL, random solenoidal force

- **Resolution**: $dx=0.01$ pc (512$^3$ and 1024$^3$ uniform grids)

- **Initial conditions**:

<table>
<thead>
<tr>
<th>$M_s$</th>
<th>$M_{A,0}$</th>
<th>$\beta_0$</th>
</tr>
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<td>31.6</td>
<td>20.0</td>
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<tr>
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<tr>
<td>10</td>
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<td>0.2</td>
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</tbody>
</table>

- **Time evolution**: 7-9 dynamical times, without self-gravity
Time evolution of the magnetic energy

- Saturation of $E_M$ below equipartition for $M_{A,0} = 10^{-30}$
- The saturation is achieved in approximately $2 \ t_{\text{dyn}}$
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 $M_S$.

Federrath et al. 2011-2014:

- Growth rate not too strongly dependent on $M_S$.
- Saturation rate strongly dependent on $M_S$. 
Slight variation of growth rate with sonic rms Mach number

Slight variation of Strong drop of saturation level growth rate with sonic rms Mach number
Compressive ratio of MC turbulence

\[ \chi \equiv \frac{\langle v_c^2 \rangle}{\langle v_s^2 \rangle} \]

\[ \chi_t \equiv \frac{[\langle v_c^2 \rangle - V_e^2]}{[\langle v_s^2 \rangle - V_r^2]} \]

- Broad lognormal distribution of the compressive ratio
- \( \langle \chi_t \rangle \approx \langle \chi \rangle \approx 0.3 \pm 0.2 \)
- Same results with gravity

SF models should account for this distribution.
Density PDF of MCs

- Individual cloud PDFs are well approximated by lognormal distributions.
- The composite PDF of all clouds is lognormal over 6 orders of magnitude in $p(s)$
- Power law tail with self-gravity
Density variance versus Mach number

\[ \sigma_s^2 = \ln(1 + b^2 \mathcal{M}^2) \]

**Ansatz:** \( b \) is the compressive fraction of the Mach number, so we define a compressive Mach number:

\[ b \mathcal{M} = \sqrt{\chi/(1 + \chi)} \mathcal{M} \equiv \mathcal{M}_c \]

Then we include the effect of the magnetic field, and define a new effective Mach number:

\[ \sigma_s^2 = \ln(1 + (\beta/(1 + \beta)) \mathcal{M}_c^2) = \ln(1 + \mathcal{M}_{e,c}^2) \]
Conclusions

- SN explosions can drive the turbulence in the dense ISM and MCs.
- While the overall ISM turbulence is trans-Alfvénic and mildly supersonic, the turbulence in the dense gas and MCs is supersonic and super-Alfvénic.
- Most power is in solenoidal modes on all scales, with $\langle \chi \rangle \approx 0.3 \pm 0.2$ in MCs.
- **SN driving is the main source of the observed MC turbulence.**
- The observed MC velocity-size and mass-size relations and mass and size probability distributions are reproduced by SN-driven turbulence.
- MC lifetimes are predicted to be of the order of two crossing times.
THANKS