What Shapes the Structure of MCs: Turbulence or Gravity?

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Motivation: Interpretations differ

Larson (1981)
\[ \sigma_u = 1.10L^{0.38} \text{km/s} \]

Solomon et al. (1987)
\[ \sigma_u = (1.0 \pm 0.1)S^{0.5 \pm 0.05} \text{km/s} \]

- Power index is similar to the Kolmogorov law of incompressible turbulence.
- Observed nonthermal linewidths originate from a common hierarchy of interstellar turbulent motions.
- Structures cannot have formed by simple gravitational collapse.

- The Kolmogorov turbulent spectrum is ruled out by the new data.
- The size-linewidth relation arises from virial equilibrium.
- MCs are in or near virial equilibrium since their mass determined dynamically agrees with other independent measurements.
- MCs are not in pressure equilibrium with warm/hot ISM.
What’s the nature of this MC conspiracy?

Let’s see what we know about turbulence and gravity…

“I soon understood that there was little hope of developing a pure, closed theory, and because of the absence of such theory the investigation must be based on hypotheses obtained in processing experimental data.”

A. N. Kolmogorov
Selected Works, 1985

Disclaimer:
Both turbulence and self-gravity are important in GMCs.
Column density maps

SIMULATION ➪
2048$^3$ isothermal HD turbulence, Mach 6

OBSERVATION ➪
Taurus MC: $^{12}$CO

[Kritsuk et al. 2009] [Goldsmith et al. 2008]

Density structures are morphologically similar overall, but…
A note of caution...

Density power spectra for two snapshots with resolution $1024^3$ points

While structures are different, power spectra appear identical.

See also Padoan et al. (2007) and $512^3$ MHD by Kowal & Lazarian (2007)
Column density PDFs

SIMULATION

$512^3 + L5 \times 4$ self-gravitating isothermal HD turbulence, Mach 6

Extended power law tail: > 2 dex in density, slope $-2.5$

OBSERVATION

Taurus: Dust extinction map

![Graph showing log10 PDF vs log10 $\Sigma/\Sigma_0$ with initial conditions $t = 0$; Deep AMR hierarchy, $t = 0.43 t_{ff}$; and effective linear resolution: $5 \times 10^5$ (5 pc – 2 AU).

Initial conditions, $t = 0$; Deep AMR hierarchy, $t = 0.43 t_{ff}$
Effective linear resolution: $5 \times 10^5$ (5 pc – 2 AU)

[Kritsuk et al., ApJL, 2011]

[Kainulainen et al., 2009]

Column density PDFs are similar
Velocity structure functions

First-order velocity SFs have similar slopes

\[ S_1(u, \ell) \equiv \langle |u(r + \ell) - u(r)| \rangle \sim \ell^{0.54 \pm 0.01} \]

\[ S_1(\ell) \sim \ell^{0.56 \pm 0.02} \]

1024^3 isothermal HD turbulence, Mach 6


First-order velocity SFs have similar slopes
Mass dimension

SIMULATION

2048$^3$ isothermal HD turbulence, Mach 6

\[ m(\ell) = m_0 (\ell/\ell_0)^{d_m} \]

\[ d_m = 2.28 \pm 0.01 \]

\[ d_m = 2.0 \] Mach 6

[Kritsuk et al., ASPC, 2009]

OBSERVATION

580 MCs from UMSB survey

\[ M = (228 \pm 18)(R^{2.36 \pm 0.04}) \]

\[ d_m = 2.36 \pm 0.04 \]

Mass dimensions are similar

[Roman-Duval et al., 2010]
What’s universal & what’s not

Is supersonic turbulence Kolmogorov or not?

\[ \nu \equiv \rho^{1/3} u \quad S_3(\nu, \ell) \propto \ell \]

\[ S_3(u, \ell) \equiv \langle |u(r + \ell) - u(r)|^3 \rangle \sim \ell^{1.27 \pm 0.02} \]

\[ S_3^\parallel(u, \ell) \text{ does not scale linearly with } \ell \text{ at } M_s = 6 \]


No, but…

Yes!

[Kritsuk et al., AIPCP, 2007]
Column density–size relation

\[ E = \langle \rho u^2 / 2 + c_s \rho \ln(\rho / \rho_0) \rangle \quad \text{Total energy is conserved} \]

\[ v \equiv \rho^{1/3} u \]

\[ S_3(v, \ell) \equiv \langle |\delta u_\ell|^3 \rangle = \langle \epsilon \rangle \ell \]

\[ \rho_\ell (\delta u_\ell)^3 \ell^{-1} \sim \sum_\ell (\delta u_\ell)^3 \ell^{-2} \sim \sum_\ell \ell^3 \zeta_1^{-2} \sim \text{const} \]

Assume \( \zeta_1 = 0.56 \pm 0.02 \) \( (\zeta_1 : S_1(u, \ell) \propto \ell^{\zeta_1}) \)

Then \( \sum_\ell \sim \ell^{2-3\zeta_1} \sim \ell^{0.32 \pm 0.06} \)

Assume \( d_m = 2.36 \pm 0.04 \)

Then \( \sum_\ell \sim m_\ell \ell^{-2} \sim \ell^{d_m-2} \sim \ell^{0.36 \pm 0.04} \)

Overall: \( \sum_\ell \propto \ell^{1/3} \)


“Math” (cont’d)

\[
\langle |\delta v_{\ell}| \rangle \sim \langle \epsilon_{\ell}^{1/3} \rangle \ell^{1/3}
\]

Intermittency \( \Rightarrow \) \( \langle \epsilon_{\ell}^{1/3} \rangle \propto \ell^{\tau_{1/3}} \)

\[ \delta u_{\ell} \ell^{-1/2} \propto \rho_{\ell}^{-1/3} \ell^{-1/6+\tau_{1/3}} \sim \sum_{\ell}^{-1/3} \ell^{1/6+\tau_{1/3}} \]

We know that \( \Rightarrow \) \( \sum_{\ell} \propto \ell^{1/3} \)

Therefore \( \Rightarrow \)

\[ \delta u_{\ell} \ell^{-1/2} \propto \sum^{1/6+3\tau_{1/3}} \]

Pan et al. (2009) \( \Rightarrow \)

\[ \tau_{1/3} \approx 0.055 \]

\[ \delta u_{\ell} \ell^{-1/2} \propto \sum^{0.33} \]

Data from Heyer et al. (2009) \( \Rightarrow \)
Where is gravity?

Projected (column) density for Mach 10 MHD-AMR turbulence simulations

Power spectra of...
- No gravity
- Self-gravitating

Super-Alfvenic

G ≠ 0

G = 0

Trans-Alfvenic

G ≠ 0

G = 0

Summary

• Supersonic turbulence alone is sufficient to explain the observed slopes of the linewidth–size and mass–size relations.
• Gravity may be important on large scales and is important on small scales.
• On small scales, formation of self-gravitating filaments and collapse of dense cores do not seem to leave detectable signature in pure velocity statistics (e.g., velocity power spectra). Why?
• Turbulence simulations predict the following approximate scaling relations for $\ell \geq 0.5$ pc, assuming weak magnetic field:

\[ S_1(u, \ell) \propto \ell^{0.55} \]

\[ m_\ell \propto \ell^{2.35} \]

\[ \sum_\ell \propto \ell^{0.33} \]

\[ \delta u_\ell \ell^{-1/2} \propto \sum^{0.33} \]
CCAT potential

- Large-area, high-resolution surveys tracing the substructure and kinematics of MCs on scales down to and below the sonic scale (~0.1pc).
- Spectral line observations are essential as they help to probe gas dynamics at scales of interest, not just the column density.
- Observations of nearby galaxies would help to examine the integral scale of MC turbulence and constrain the major energy injection mechanisms.
- Zeeman measurements of $B_\parallel$ combined with linear polarization measurements of $B_\perp$ would be extremely useful for constraining magnetic field properties in star formation models.