Effects of Magnetic Fields on the Formation of Molecular Clouds

with

Lee Hartmann & Jim Stone
Spitzer (IRAC & MIPS), GLIMPSE (l,b) = (14.2,-0.5)
FH, Whitney, Indebetouw et al., in prep.

frothy
fuzzy
filamentary
turbulent
fragmented
clumpy
messy
self-similar \[d(\log N)/d(\log M) \approx -0.8\]

...
Solar Neighborhood: Rapid Star Formation & Short-lived Clouds

- Most molecular clouds form stars. Spitzer c2d, GLIMPSE, ...
- Molecular clouds have young (1-2 Myr) stellar populations.
- Stars > 3 Myr are not associated with molecular gas.

### Star-forming regions

<table>
<thead>
<tr>
<th>Region</th>
<th>( \langle t \rangle^* ) (Myr)</th>
<th>Molecular Gas?</th>
<th>Ref. (age)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coalsack</td>
<td>...</td>
<td>Yes</td>
<td>...</td>
</tr>
<tr>
<td>Orion Nebula</td>
<td>1</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>Taurus</td>
<td>2</td>
<td>Yes</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>Oph</td>
<td>1</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>Cha I, II</td>
<td>2</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>Lupus</td>
<td>2</td>
<td>Yes</td>
<td>1</td>
</tr>
<tr>
<td>MBM 12A</td>
<td>2</td>
<td>Yes</td>
<td>4</td>
</tr>
<tr>
<td>IC 348</td>
<td>1–3</td>
<td>Yes</td>
<td>1, 4, 5, 6</td>
</tr>
<tr>
<td>NGC 2264</td>
<td>3</td>
<td>Yes</td>
<td>...</td>
</tr>
<tr>
<td>Upper Sco</td>
<td>2–5</td>
<td>No</td>
<td>1, 6, 7</td>
</tr>
<tr>
<td>Sco OB2</td>
<td>5–15</td>
<td>No</td>
<td>8</td>
</tr>
<tr>
<td>TWA</td>
<td>( \sim 10 )</td>
<td>No</td>
<td>9</td>
</tr>
<tr>
<td>( \eta ) Cha</td>
<td>( \sim 10 )</td>
<td>No</td>
<td>10</td>
</tr>
</tbody>
</table>

* Average age in Myr.

Gravity in finite, pressure-less clouds:

free-fall time of a spherical cloud of uniform density:

$$\tau_{ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

→ independent of radius
→ Material from edge arrives at same time at center as material close to center.
→ Linear density perturbations will be swept up in global collapse.

similar for sheets and filaments of uniform density  Burkert & Hartmann 2004

Massive stars form only rarely (if at all) in “isolation”.
Chu & Gruendl 2008

Rapid star formation requires non-linear density seeds arising during cloud formation.
A possible answer: Ballesteros-Paredes et al. 1999, Hartmann et al. 2001

The properties of molecular clouds are a direct consequence of their formation process.

Molecular clouds form in converging flows of atomic hydrogen.

Combination of thermal and dynamical instabilities leads to substructure and non-linear seeds for rapid local action of gravity.

→ prevention of global collapse.

FH et al. 05, 06, 08;
see also Audit & Hennebelle 05, Hennebelle et al. 07a,b
Vazquez-Semadeni et al. 06, 07, Koyama & Inutsuka 04,08
A numerical experiment: the extreme view.

Two uniform, identical flows colliding head-on at interface with large-scale geometric perturbation in non-periodic domain.

→ turbulence generation “from scratch” (no “driven turbulence”)
→ avoid Wypiiwygo-problem

→ global gravitational effects

“most unfavorable conditions”
Non-linear Thin Shell Instability (Vishniac 1994)

- lateral momentum transport
- ram pressure imbalance at peaks/troughs


growthrate \[ \omega \sim c_s k (k\Delta)^{1/2} \]
Non-linear Thin Shell Instability (Vishniac 1994)

- lateral momentum transport
- ram pressure imbalance at peaks/troughs

\[ \omega \sim c_s k (k \Delta)^{1/2} \]

- magnetic fields reduce growthrate
- fields can suppress NTSI if

\[ \rho u^2 \sin \alpha \cos \alpha < B^2/2 \]

FH et al. 2007
Kelvin-Helmholtz Instability

shear flows result from deflected inflow

\[ \omega \sim k \left( U^2 - c_A^2 \right)^{1/2} \]

incompressible growth rate

MHD-KHI
Palotti, FH, Zweibel & Huang 2008.
Regime: transition from

<table>
<thead>
<tr>
<th>warm ionized medium (WIM)</th>
<th>to</th>
<th>cold neutral medium (CNM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n  ≈ 1 cm⁻³</td>
<td></td>
<td>warm neutral medium</td>
</tr>
<tr>
<td>T  ≈ 8500 K</td>
<td></td>
<td>thermally unstable regime</td>
</tr>
<tr>
<td>c_s  ≈ 10 km s⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mach  ≈ 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B  ≈ 5 µG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n  ≈ 100 cm⁻³</td>
<td></td>
<td>T  ≈ 40 K</td>
</tr>
<tr>
<td>c_s  ≈ 2 km s⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mach  ≈ 3</td>
<td></td>
<td>B  ≈ 5-10 µG</td>
</tr>
</tbody>
</table>

Heiles & Troland 2003, 2005
Thermal Instability  

Net cooling rate:  \( \mathcal{L}(n, T) \equiv n\Gamma - n^2\Lambda(T) \) [erg s\(^{-1}\) cm\(^{-3}\)]

- photo-electric heating on grains
- collisionally excited atomic line coolants

condensation mode

Scales:
- lower scale: heat conduction \((10^{-3} \ldots 10^{-2}\) pc\)
- upper scale: sound crossing scale \((10\text{pc})\):  \( \lambda_c = \tau_c c_s \) (isobaric \(\rightarrow\) isochoric)
**Thermal Instability**

Net cooling rate:

\[ \mathcal{L}(n, T) \equiv n \Gamma - n^2 \Lambda(T) \quad [\text{erg} \, s^{-1} \, \text{cm}^{-3}] \]

- photo-electric heating on grains
- collisionally excited atomic line coolants

**Cooling function**

Dalgarno & McCray 1972
Sutherland & Dopita 1993
Wolfire et al. 1995, 2003

**Thermal Equilibrium curve:** \( P \propto n^\gamma \)

- WNM, atomic
- CNM, atomic, molecular
- WIM, atomic

**Regime**

- NTSI
- KHI
- TI

**Consequences**

**Mechanism**

- Forming Clouds
- Physics

**Regime**

- NTSI
- KHI
- TI
The Side View (hydro!)

- pile-up of material
- thermal fragmentation
- local gravitational collapse
- global gravitational collapse

\[ n = 3 \text{ cm}^{-3} \]
\[ v = 9 \text{ km s}^{-1} \]

3D at 256 x 512 x 512

19 < \log N [\text{cm}^{-2}] < 23

FH et al. 2008
<table>
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<th>Physics</th>
<th>The Heresy</th>
</tr>
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<tr>
<td></td>
<td></td>
<td>Cooling, Gravity &amp; Geometry</td>
</tr>
</tbody>
</table>

View along inflow (hydro again!)

**blue/green:**
thermal fragmentation

**red/yellow:**
local collapse

**filament:**
global collapse

$n = 3 \text{ cm}^{-3}$
$v = 9 \text{ km s}^{-1}$

3D at 256 x 512 x 512
$19 < \log N [\text{cm}^{-2}] < 23$

FH et al. 2008

**Thermal fragmentation seeds local collapse before global collapse.**
### Standard scenario of flow-driven cloud formation:
- selection effect for molecular cloud formation
- material collected over large distances along field lines: fields as “tracks”
- perpendicular field component negligible

Hartmann et al. 2001, Bergin et al. 2004

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### Problem:
**Essentially 1D treatment.**

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### Role of magnetic fields in > 1D?
Lesser god in Greek mythology, also known as “The Old Man of the Sea”. He lives in the sea off the coast of Egypt and can see things in the past, presence and future, but is very unwilling to share his knowledge. To evade questions, he has the ability to change his appearance (hence “protean”).

However, if you managed to catch and hold him, he would assume his true shape and answer your questions.
Proteus (the code)
in collaboration with A. Slyz & J. Devriendt (Oxford)

- gas-kinetic solver
- 3D viscous hydrodynamics and non-ideal magnetohydrodynamics
- two-fluid description of ambipolar drift
- (self-)gravity (periodic/non-periodic)
- Eulerian and Lagrangian tracers
- fully parallelized

*ideal for converged evolution of HD/MHD instabilities*

- dissipative terms at no extra cost and at same spatial and temporal order
  → explicit control of dissipative effects
  → viscosity independent of grid geometry
- non-ideal magnetohydrodynamics:
  Ohmic resistivity via resistive fluxes
  → accurate advection & evolution of complex field geometries
- low intrinsic numerical diffusion
Isothermal NTSI, densities:

field \parallel inflow

c_A/c_s = 1.0

FH et al. 2007
### Isothermal NTSI, densities:

**field \perp inflow**

**log density**

**log magnetic energy density**

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<tr>
<td></td>
<td></td>
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<td>Early Teachings</td>
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<tr>
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<tr>
<td></td>
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<td>New Revelations</td>
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N=2048
Isothermal NTSI, densities:

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<td>New Revelations</td>
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</tbody>
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<table>
<thead>
<tr>
<th></th>
<th>( c_A/c_s = 0.5 )</th>
<th>( c_A/c_s = 1.0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>N=512</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>N=1024</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>N=2048</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
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While the NTSI is suppressed, substructure can still form.
Isothermal converging flows: B-n relation

lateral transport of gas breaks B-n relation

FH et al. 2007
Now **3D & thermal effects**, but **no field** again…

**strong fragmentation**

\[ n_0 = 3 \text{ cm}^{-3} \]
\[ v_0 = 9 \text{ km s}^{-1} \]

**column density projections**
The same, but now with field \textit{parallel} to flow…

organized filaments, suppression of NTSI/KHI

\[
P = Q + iU = N \int f(y) \frac{(B_x + iB_z)^2}{B_x^2 + B_z^2} \cos^2 \gamma dy
\]

\[
\cos^2 \gamma = \frac{B_x^2 + B_z^2}{B_x^2 + B_y^2 + B_z^2}
\]

\[
\beta_0 = 2, \quad B_0 = 2 \mu G \\
n_0 = 3 \text{ cm}^{-3} \\
v_0 = 9 \text{ km s}^{-1}
\]
The same, with field *perpendicular* to flow...

exchange modes allow some growth of substructure

\[ P = Q + iU = N \int f(y) \left( \frac{B_x + iB_z}{B_x^2 + B_z^2} \right)^2 \cos^2 \gamma \, dy \]

\[ \cos^2 \gamma = \frac{B_x^2 + B_z^2}{B_x^2 + B_y^2 + B_z^2} \]

\[ \beta_0 = 200, \, B=0.2 \mu G \]

\[ n_0 = 3 \text{ cm}^{-3} \]

\[ v_0 = 9 \text{ km s}^{-1} \]
The Modeler’s F-word (actually, R-word)

NTSI

NTSI suppressed in favor of cooling

NTSI saturated by turbulence

laminar flow
unresolved cooling length
unresolved Field length

ISM

transition to turbulence

> 4 orders of magnitude

log E

log k

The Church
- Early Teachings
- Isothermal
- New Revelations

The Heresy

Physics

The Church

Forming Clouds
The B-n relation in 3D including thermal effects…

field parallel to inflow

field perpendicular to inflow
In the context of Rapid Star Formation:

**Clouds:**
need non-linear density perturbations early on.
*Cloud structure (and properties) must arise during formation process (and not as “afterthought”).*

**Flow-driven cloud formation:**
rapid fragmentation due to combination of strong thermal and dynamical instabilities.

**Magnetic fields:**
- reduce growth of dynamical instabilities (in 3D)
- lead to large-scale coherent filaments
- may lead to selection effect for cloud formation
  - \( B(n) \) relation is generally weak, independent of mean field orientation