High-Resolution Simulations of Shocks/Winds interacting with Fractal Clouds in the Interstellar Medium

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Brief Review: Shock/Wind-Cloud Problem

Classical (Magneto)Hydrodynamics Problem:

Klein, McKee and Colella 1994: 2.5D HD simulations, convergence study, strong shocks
Gregori et. al. 2000: 2D MHD simulations, uniform magnetic fields
Poludnenko et. al. 2002: Shocks interacting with multiple clumps (2D MHD)
Fragile et. al. 2005, Orlando et. al. 2008: Radiative Cooling and thermal conduction
Nakamura et. al. 2006: Smooth cloud boundaries (2D HD)
Cooper et. al. 2009: Clouds interacting with starburst-driven winds (3D HD+cooling)
Li 2012, 2013: Self-contained magnetic fields (3D MHD+cooling)

Unexplored parameter space:
High-Density Contrasts (>100) in HD Adiabatic Simulations
Convergence Study with Fractal Clouds (Non-Uniform density profiles)
Effects of Cooling and Magnetic field topologies in 2D at high resolution

Applications
Filamentary Structures in the ISM
Motivation: Galactic Centre Non-thermal Filaments

Narrow and long structures.

Synchrotron-emitting structures.

Non-thermal, highly polarised (Lang et. al. 1999)

\[ F_\nu \propto \nu^\alpha \]

Magnetic Field along the filament: \( \sim 1mG \)

Spectral indices below 1.4GHz:

Some of them have kinks.

\(-0.6 < \alpha < -0.4\)

Radio image at 90cm of the inner 200 parsecs of the Milky Way (LaRosa et. al. 1999), Northern and southern plumes (Haynes et. al. 1992), Survey of Non-thermal Filaments (Yusef-Zadeh et. al. 2004)
2D Simulation Setup

**Initial Conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Number Density</td>
<td>$n_w$</td>
<td>$cm^{-3}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Wind Velocity</td>
<td>$v_w$</td>
<td>$kms^{-1}$</td>
<td>500</td>
</tr>
<tr>
<td>Average Cloud Number Density</td>
<td>$n_c$</td>
<td>$cm^{-3}$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Cloud Velocity</td>
<td>$v_c$</td>
<td>$kms^{-1}$</td>
<td>0</td>
</tr>
<tr>
<td>Cloud Radius</td>
<td>$r_c$</td>
<td>$pc$</td>
<td>6</td>
</tr>
<tr>
<td>Average Cloud Temperature</td>
<td>$T$</td>
<td>$K$</td>
<td>$10^3$</td>
</tr>
</tbody>
</table>

**Boundary Conditions**

$$\frac{\partial [\text{variable}]}{\partial N} = 0$$

Outflow Conditions and Inflow Condition

$$\rho(r) = k \times \left( \rho_0 + \frac{(\rho_c - \rho_0)}{1 + \left( \frac{r}{r_c} \right)^n} \right)$$

$n = 12$

$$P(\rho) = 0.00026497 \cdot e^{-\frac{(\ln \rho - 1016.1513)^2}{4533906.5178}}$$
### Hydrodynamics and Cloud Disruption Study

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Simulation Timescale</strong></td>
<td>$T = \tau * t_0 = \tau * \frac{x_0}{v_0} = 2.5\text{Myr}$</td>
</tr>
<tr>
<td><strong>Cloud Crushing Time</strong></td>
<td>$t_{cc} = \left( \frac{\rho_c}{\rho_w} \right)^{\frac{1}{2}} \frac{r_c}{M_s c_s} = 0.25\text{Myr}$</td>
</tr>
<tr>
<td><strong>Cooling Time</strong></td>
<td>$t_{cool} = \frac{3}{2} n k_B T}{n^2 \Lambda} = 0.655\text{kyr}$</td>
</tr>
<tr>
<td><strong>Kelvin-Helmholtz timescale</strong></td>
<td>$t_{KH} = \frac{r_c (\rho_c + \rho_w)}{(v_w - v_c) (\rho_c \rho_w)^{\frac{1}{2}}} = 0.2\text{Myr}$</td>
</tr>
<tr>
<td><strong>Def: Mass-weighted quantities</strong></td>
<td>$\langle f \rangle = \frac{1}{M_{cl}} \int f C \rho dV$</td>
</tr>
</tbody>
</table>

### Magneto(Hydrodynamics) and Cloud Disruption Study

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<tbody>
<tr>
<td><strong>Plasma Beta</strong></td>
<td>$\beta = \frac{2P}{B^2}$</td>
</tr>
</tbody>
</table>
Convergence Study

\[ \lim_{h \to 0} \frac{u(x+h) - u(x)}{h} = u'(x) \]

\[ R \]

\[ dV \]

\[ \frac{R}{C} \]

\[ \frac{R}{C} \cdot dV \]

\[ \times 10^5 \ yr \]

\[ \text{Average Cloud Density} \]

\[ \times 10^5 \ yr \]

\[ f_{\text{mix}} = \frac{M_{\text{mix}}}{M_{\text{cl}}} \]

\[ R \]

\[ \frac{R}{C} \]

\[ \frac{R}{C} \cdot dV \]

\[ \times 10^5 \ yr \]

\[ \text{Mass Flux through } y=50\text{pc:} \]

\[ F = \int \rho v_y dS \]

\[ F \times 3 \times 10^{-3} \frac{M_{\odot}}{yr} \]

\[ r=\text{cloud radius} \]

\[ C=\text{colour parameter} \]

\[ C_{\text{mix}}=\text{colour mixed gas} \]

\[ 0 \leq C \leq 1 \]

\[ 0.1 \leq C_{\text{mix}} \leq 0.9 \]
Convergence Study

Average Cloud Density

\[ \rho_{av} = \frac{\int C \rho dV}{\int CdV} \times 10^3 \text{yr} \]

- \( r = \text{cloud radius} \)
- \( C = \text{colour parameter} \)
- \( C_{mix} = \text{colour mixed gas} \)

\[ 0 \leq C \leq 1 \]
\[ 0.1 \leq C_{mix} \leq 0.9 \]
Convergence Study

Moments of Inertia

\[ a = \left[ 5 \left( \langle x^2 \rangle - \langle x \rangle^2 \right) \right]^{\frac{1}{2}} \]
\[ b = \left[ 5 \left( \langle y^2 \rangle - \langle y \rangle^2 \right) \right]^{\frac{1}{2}} \]

Shape Parameter:

\[ Shape = \frac{b}{a} \]

At least 60 cells/r for convergence

Significant Elongation Shape \( \sim 3 \)

Cloud disruption is dominated by instabilities.
Hydrodynamics Study:
Effects of Cloud Geometry

Uniform Cloud (UC)
Resolution 120 cells/r

Fractal Cloud (FC)
Resolution 120 cells/r

Average Cloud Density

Mixing Fraction
Average Cloud Density
$n \times \text{cm}^{-3}$

$M_{\text{mix}} = M_{\text{cl}} \mapsto dV$
$R_{\text{C}} \mapsto dV$

Graph showing the density distribution for UC and FC.
Velocity Dispersions & Vortensity
Uniform Cloud (UC) vs Fractal Cloud (FC)

\[
\sigma_x = \left[ \langle v_x^2 \rangle - \langle v_x \rangle^2 \right]^{\frac{1}{2}}
\]

\[
\sigma_y = \left[ \langle v_y^2 \rangle - \langle v_y \rangle^2 \right]^{\frac{1}{2}}
\]

\[
\sigma = 10^2 \text{ km s}^{-1}
\]

\[
t = 2.0 \text{ Myr}
\]

Vortensity: \( w^2 = (\nabla \times \mathbf{v})^2 \)
Hydrodynamics Study
Effects of Cooling

Adiabatic Simulation
Resolution 120 cells/r
Γ = 1.667

Quasi-Isothermal Simulation
Resolution 120 cells/r
Γ = 1.001

x-Component Velocity Dispersion

\[ \sigma \times 10^2 \frac{km}{s} = \left[ \langle v_x^2 \rangle - \langle v_x \rangle^2 \right]^{\frac{1}{2}} \]

Mass Flux through y = 50 pc:
\[ F \times 3 \times 10^3 M_{\odot} \]

x-Component Velocity Dispersion
\[ \times 10^2 \text{ km s}^{-1} \]

\( t \times 10^5 \text{ yr} \)
Effects of Cooling
Adiabatic Sim. (ADIAB) vs Quasi-Isothermal Sim. (QISOT)

Moments of Inertia
\[ a = \left[ 5 \left( \langle x^2 \rangle - \langle x \rangle^2 \right) \right]^{\frac{1}{2}} \]
\[ b = \left[ 5 \left( \langle y^2 \rangle - \langle y \rangle^2 \right) \right]^{\frac{1}{2}} \]

Shape Parameter:
\[ \text{Shape} = \frac{b}{a} \]

Evidence of filaments with:
- Shape \( \sim 8 \)
- Lifetime \( \sim 10^5 \text{ yr} \)
- KH, RT instabilities are suppressed
- Wake is less turbulent
Magnetohydrodynamics Study
Effects of Parallel Magnetic Field

$\beta = 100$

HD QISOT Simulation
Resolution 120cells/r

Filaments

MHD QISOT Simulation
Resolution 120cells/r

$t \times 10^5 \text{yr}$
Magnetohydrodynamics Study
Effects of Parallel Magnetic Field

MHD QISOT Simulation (Fractal Clouds)
Resolution 120 cells/r

\[ \beta = 100 \]
\[ t \sim 1 \text{ Myr} \]

Transverse component changes dynamics.

3D simulations are needed to study oblique fields.

\[ Syn \propto B^{\frac{3}{2}} \ast \rho \]
Summary

4-phase process:
1. Blast wave produces shocks.
2. Shock compression - cloud flattens
3. Re-expansion phase - rarefaction at the rear

Conclusions

High-Density Contrasts (>100) require 120 cells per cloud radius. Fractal Clouds favour instabilities and elongation thus surviving longer. Filamentary Structures arise for all magnetic field topologies.

<table>
<thead>
<tr>
<th></th>
<th>Observations</th>
<th>Simulations</th>
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<tbody>
<tr>
<td>Shape (Length/Width)</td>
<td>10 – 100</td>
<td>5 – 8</td>
</tr>
<tr>
<td>Lifetime</td>
<td>10 – 100 kyr</td>
<td>100 kyr</td>
</tr>
<tr>
<td>Magnetic Field NTF</td>
<td>0.1 – 1 mG</td>
<td>0.2 mG</td>
</tr>
<tr>
<td>Ambient Magnetic Field</td>
<td>10 – 100 µG</td>
<td>2 µG</td>
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</table>