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Magnetohydrodynamic fragmentation

From clouds to dense cores

Sven Van Loo, Sam Falle and Tom Hartquist

Overview

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- Introduction
- Formation of molecular clouds
- Dense core formation in clouds
- Effect of ambipolar diffusion
- Conclusions

Introduction

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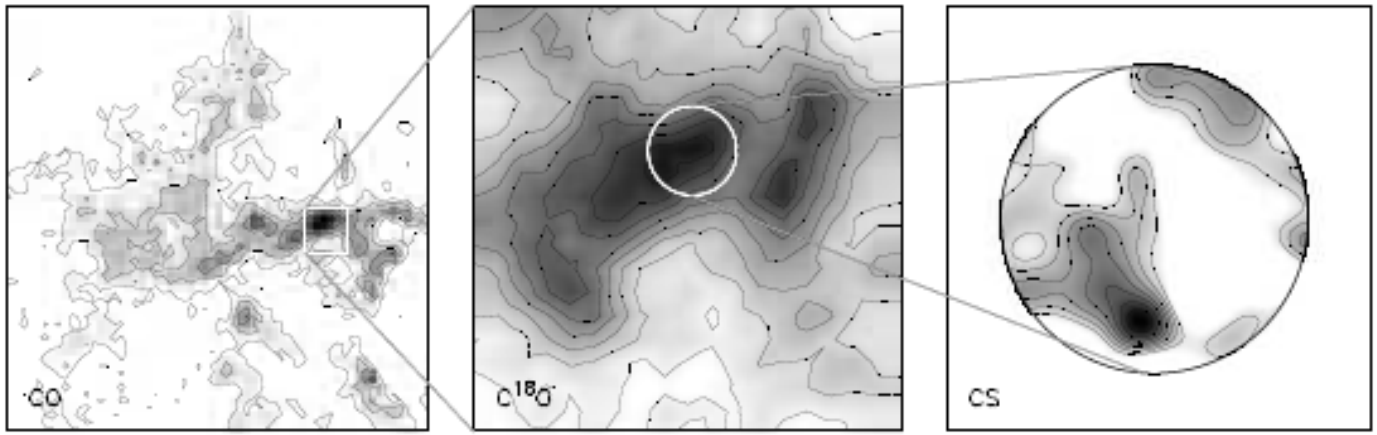
Hierarchical density structure in molecular clouds

- Not homogeneous, but highly structured
- Stars embedded in dense cores



Emission line maps of the Rosette Molecular Cloud (Blitz 1987)

- MCs that do not harbour any young stars are rare
- Old stellar associations (few Myr) are devoid of molecular gas

 Cloud and core formation are entangled

Cloud formation

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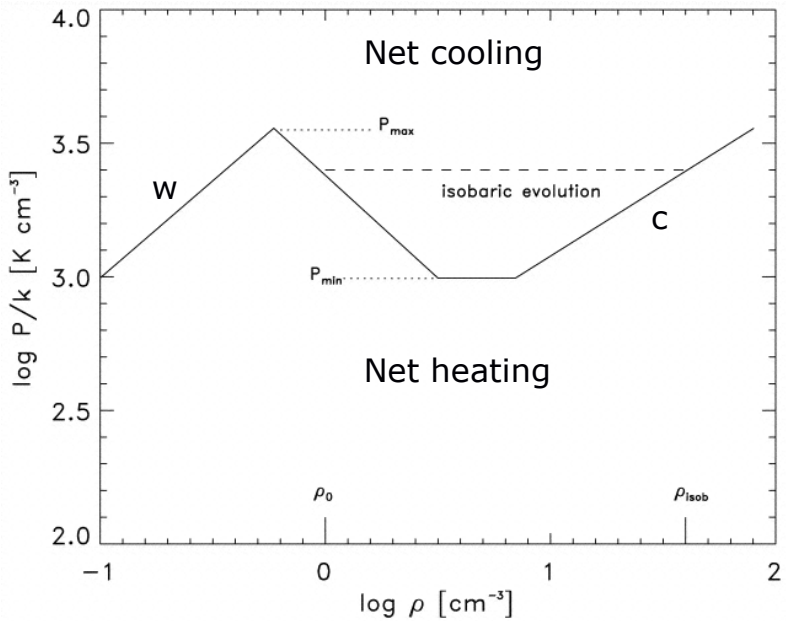
Compression +

Thermal processes in diffuse atomic gas:

- Heating: photoelectric heating, cosmic rays, soft X-rays, …
- Cooling: fine-structure lines, electron recombination, resonance lines, …

⇒ 2 stable phases in which heating balances cooling:

1. Rarefied, warm gas (w; T > 6102 K)
2. Dense, cold gas (c; T < 313 K)



(Sanchez-Salcedo et al. 2002)

Cloud formation: flow-driven

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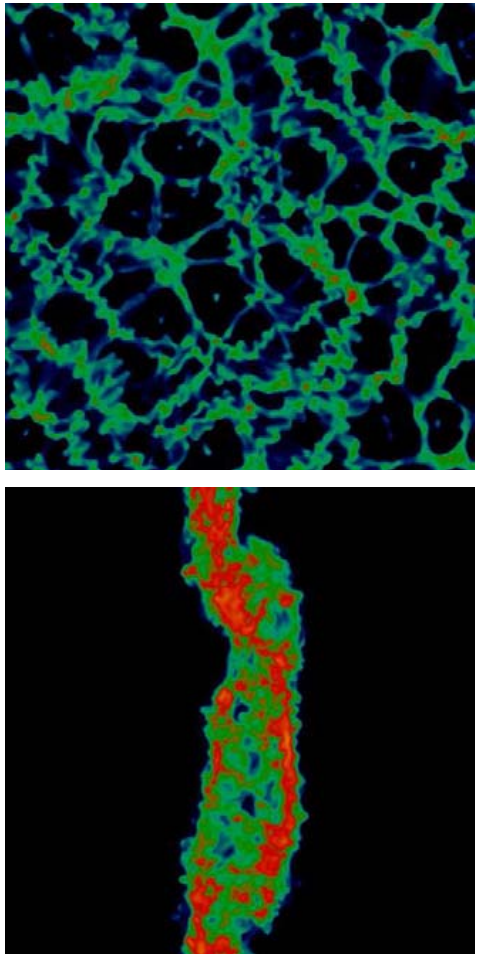
Flow-driven formation or colliding streams

Heitsch, Stone & Hartmann (2009)
Hennebelle et al. (2008)

e.g. expanding and colliding supershells

- Collision region prone to instabilities, i.e. KH, RT, NTSI
- Turbulent shocked layer
- Fragmentation into cold clumps
- Structure depends strongly on magnetic field (both orientation and magnitude)



Cloud formation: shock-driven

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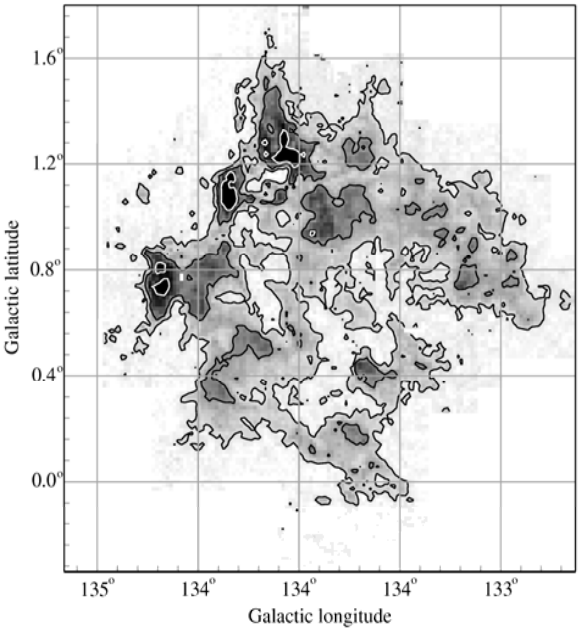
Shock-driven formation

Inutsuka & Koyama (2006)
Van Loo et al. (2007)

e.g. shocks and winds sweeping up material

- Similar processes as flow-driven
- Can explain different cloud morphologies e.g. filamentary, head-tail,…



W3 GMC (Bretherton 2003)

- Shock-cloud interaction

Previous work:

2D:	adiabatic:	MacLow et al. (1994), Nakamura et al. (2006)
	radiative:	Fragile et al. (2005), Van Loo et al. (2007)
3D:	adiabatic:	Stone & Norman (1992), Shin, Stone & Snyder (2008)
	radiative:	Leão et al. (2009) (nearly isothermal)

Numerical simulation

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Interaction of shock (M = 2.5) with initially warm, thermally stable cloud ($n = 0.45\ cm^{-3}$, T = 6788K, R = 200pc) which is in pressure equilibrium with hot ionised gas ($n = 0.01\ cm^{-3}$, T = 282500K) and $\beta = 1$.

<u>Numerics</u>:

- Ideal MHD code with AMR (Falle 1991):

  2nd order Godunov scheme with linear Riemann solver

  + divergence cleaning algorithm (Dedner et al. 2002)

- Include cooling as source function: exponentially fitted Euler method

$$\mathcal{L}(T_n) \rightarrow \mathcal{L}(T_n)\frac{e^{A\Delta t}-1}{A\Delta t} \qquad \text{where } A = d\mathcal{L}/dT$$

 improvement on stability of scheme

- Resolution: 120 cells across initial cloud radius

Dynamical evolution: parallel

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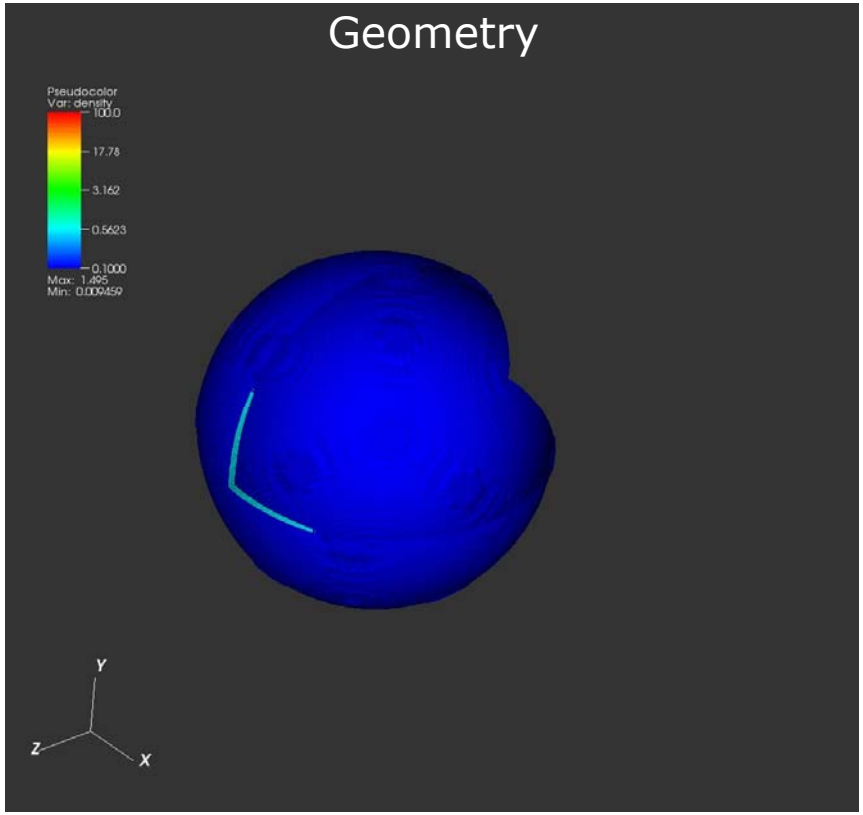
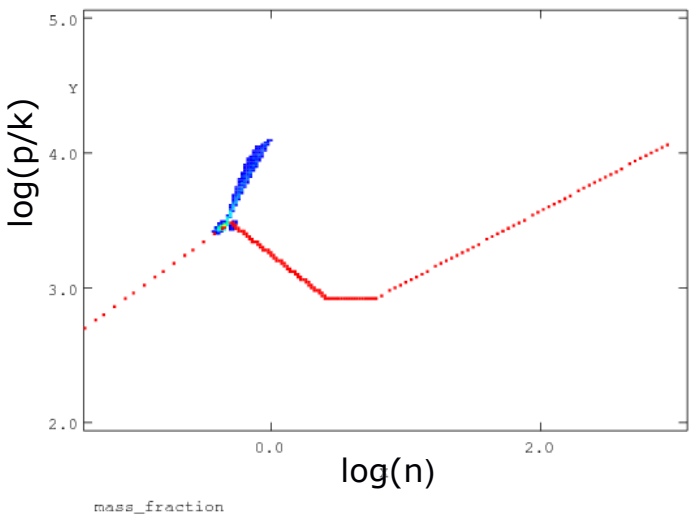
Parallel shock



Phase diagram



- Rapid condensation at boundary

Dynamical evolution: oblique

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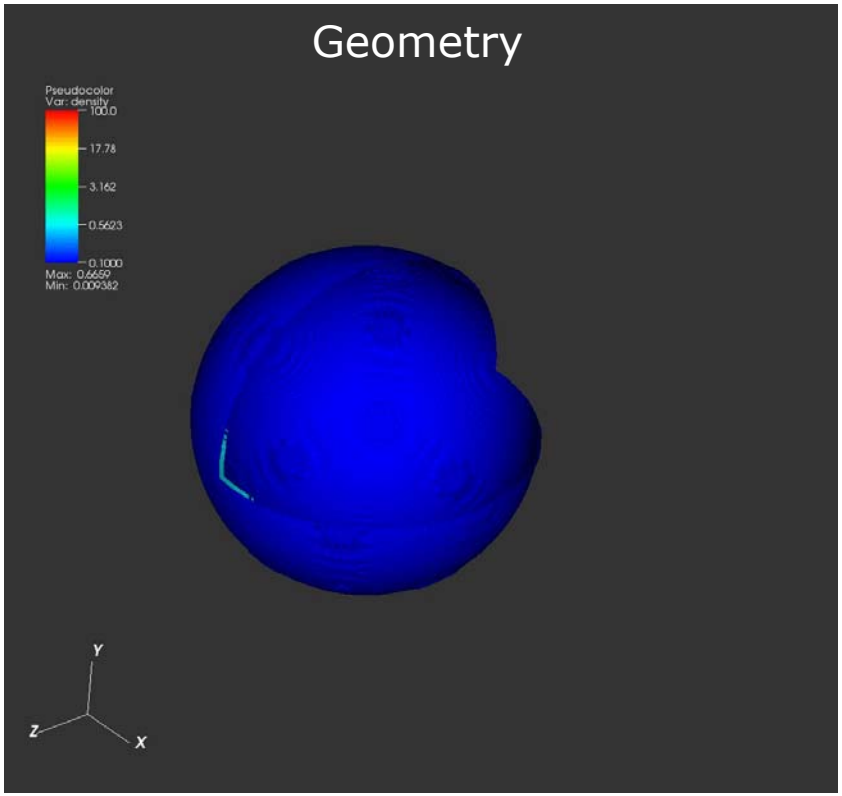
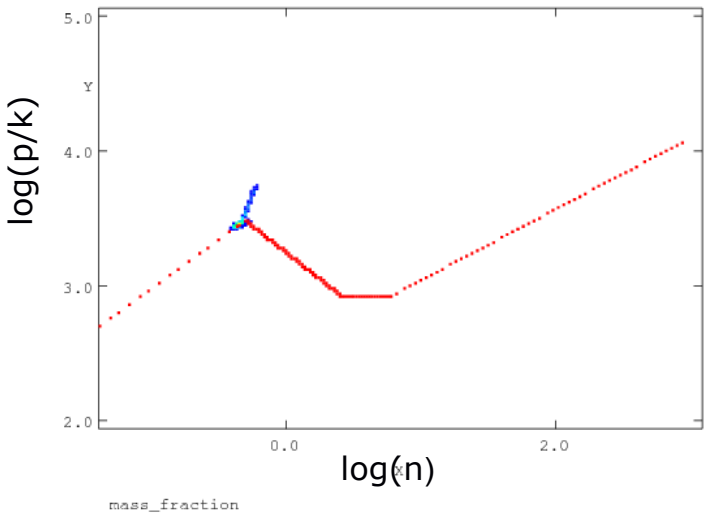
Oblique shock ~45°

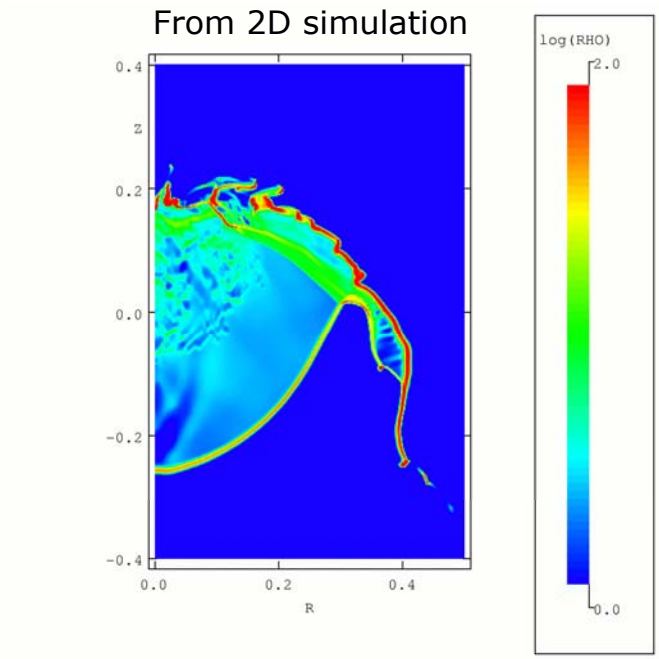


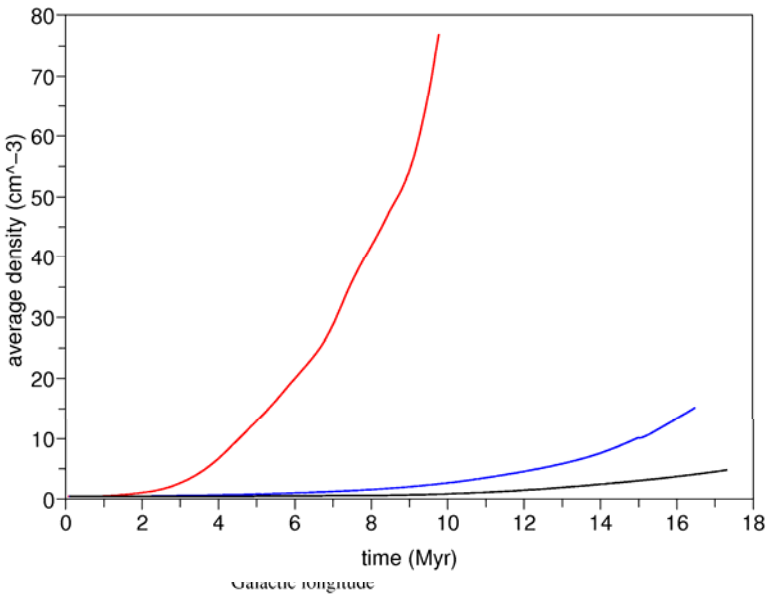
Phase diagram



- Condensation along equilibrium curve

Dynamical evolution





- Typical GMC values: $n \approx 20\ cm^{-3}$ & $R \approx 50$ pc
- High-mass clumps in boundary and low-mass clumps inside cloud $\Rightarrow$ precursors of stars
- Similar to observations of e.g. W3 GMC (Bretherton 2003)

Results of models

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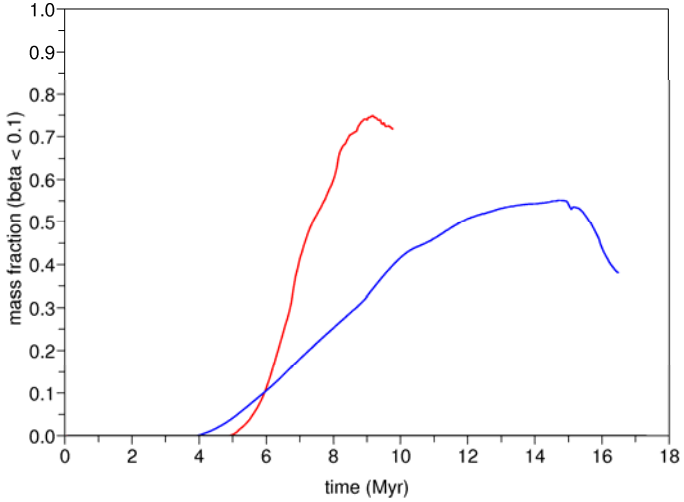
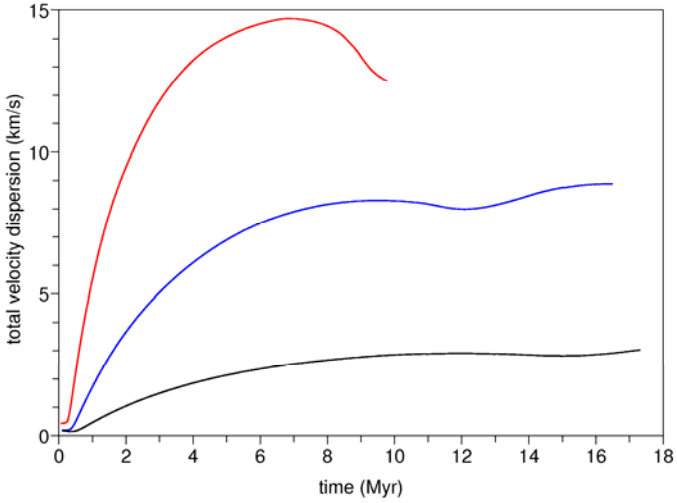
Properties of clouds

- Large fraction of cloud magnetically dominated
- High velocity dispersions

□ Ideal conditions for the formation of dense cores by MHD waves





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Details of the formation process

Analysis of Falle & Hartquist (2002):

- Slow-mode waves produce large contrasts in low-β plasma

  for a«c_a

  δv

  δρ

$$\left(\rho, \pm\frac{aB_x}{B}, \pm\frac{aB_y}{B}, -\frac{\rho a^2 B_y}{B^2}\right)$$

  small velocity perturbation ⇒ large density contrast
- Ceases to be effective when β is close to unity
- Excitation of slow-mode waves by fast-mode wave

Ambipolar resistivity

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Low ionisation fraction in clumps

- Plasma and magnetic field weakly coupled
  - $\Rightarrow$ charged particles drift through neutrals
  - $\Rightarrow$ ambipolar diffusion (Mestel & Spitzer 1956)

- Dissipation length

$$l_{AD} \approx 0.05\,pc\left(\frac{c_A}{3km/s}\right)\left(\frac{10^{-6}}{X_e}\right)\left(\frac{10^3\,cm^{-3}}{n_H}\right)$$

$\Rightarrow$ Significant effect on the observed structure in star formation

Ambipolar resistivity:model

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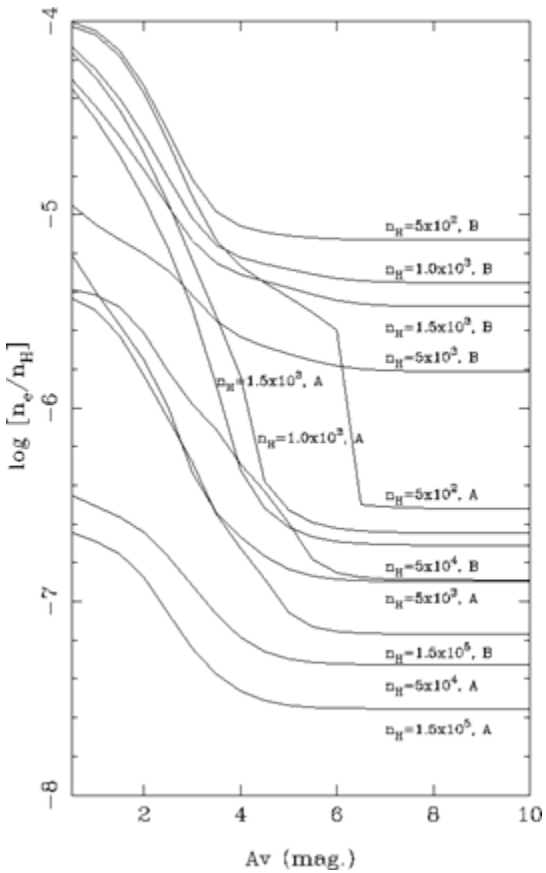
Numerical model

- Multifluid MHD code (Falle 2003) including ambipolar and Hall resisitivity (+ AMR)
- Follow the evolution of a fast-mode wave

- Ionisation fraction ~ $1/n_H$

$$X_e \approx 10^{-4} \text{ for } n_H \leq 10^3 \text{ cm}^{-3}$$

$$X_e \approx 10^{-7} \text{ for } n_H = 5\text{x}10^4 \text{ cm}^{-3}$$



(Ruffle et al. 1998)

Ambipolar resistivity:simulations

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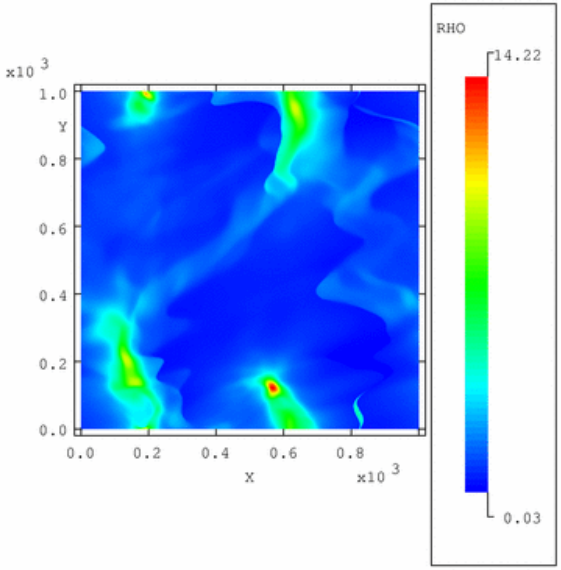
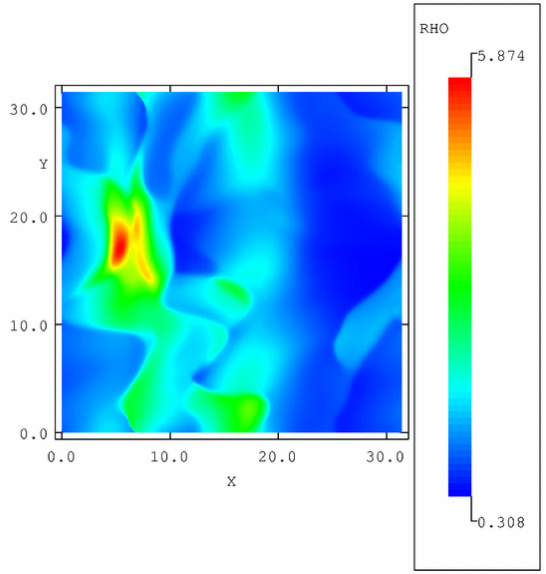
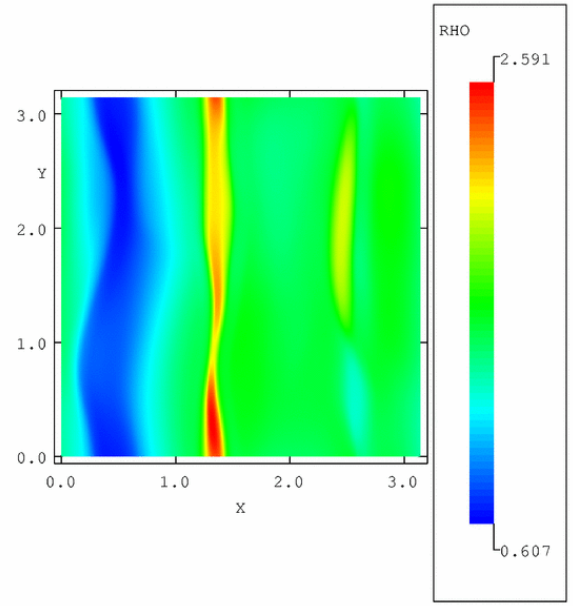
- Identical initial conditions, but different wavelengths



$\lambda = 10^4\ l_{AD}$
no wave dissipation
$\Rightarrow$ ideal MHD



$\lambda = 10^3\ l_{AD}$



$\lambda = 10^2\ l_{AD}$

Effect of ambipolar resistivity

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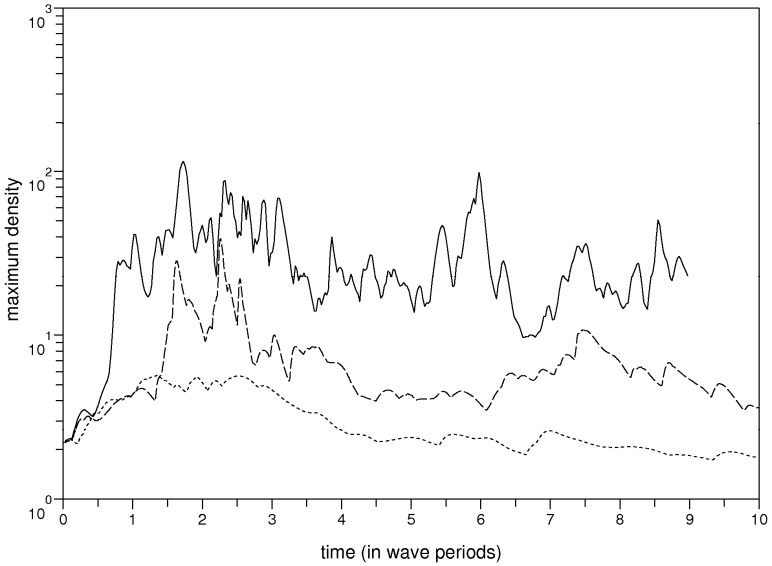
Results:

- Dense cores associated with slow-mode waves
- $\lambda = 10^4\, l_{AD}$ (clump size): dense cores with $n_H \approx 10^4 - 10^5$ cm^{-3} and sizes of order 0.1 pc
- $\lambda = 10^2\, l_{AD}$ (core size): small density contrasts + rapid decay of fast-mode wave



- Ambipolar diffusion suppresses core formation

Conclusions + future work

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Conclusions:

- Magnetically-dominated clouds form due to thermal instability and compression by weak or moderately-strong shocks
- MHD waves generate dense cores with ambipolar diffusion limiting the core size

Future work:

- Including self-gravity in the models
- The effect of multiple clouds and cloud-cloud collisions