Shock propagation through multiphase media

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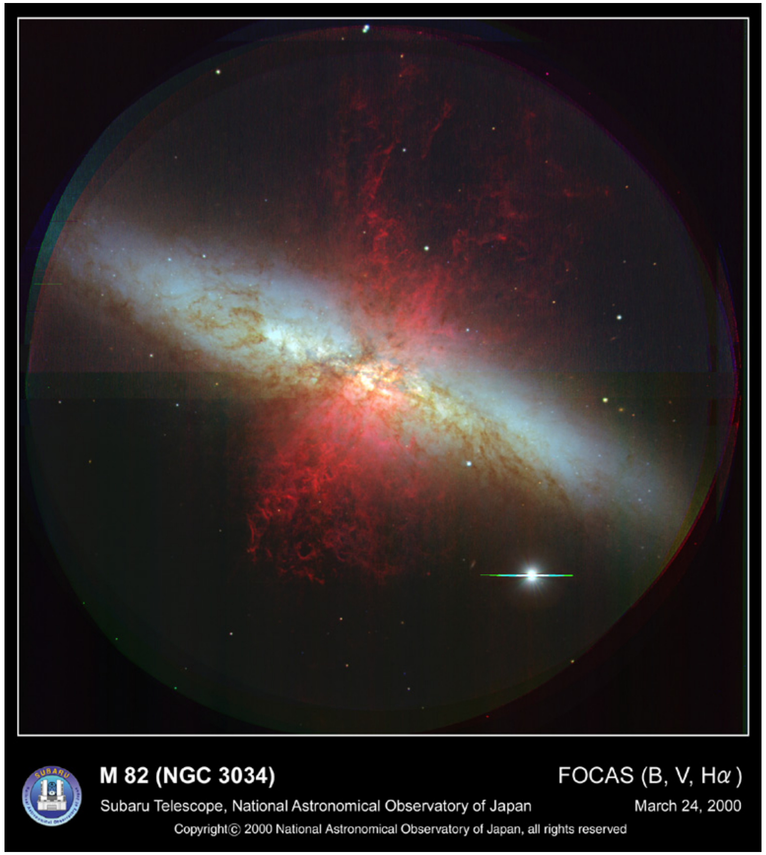
Outline

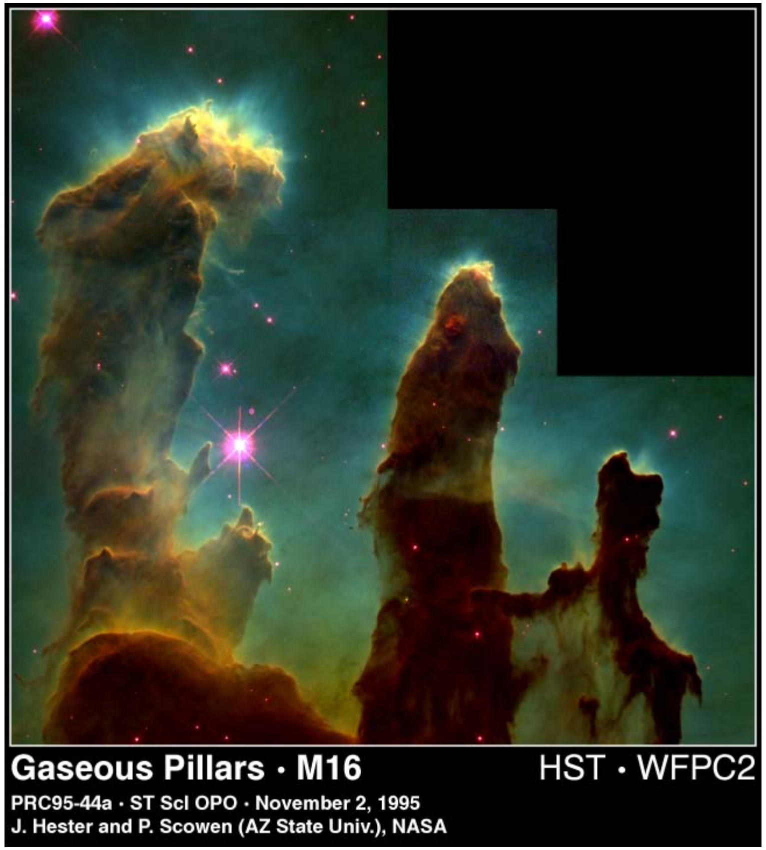
- Multiphase flows
- Previous studies
- Present work
  - 2D AMR simulations
  - 3D simulations
  - 1D characteristics
- Experimental comparisons

Astrophysical multiphase flows



Starburst galaxy M82

Astrophysical multiphase flows

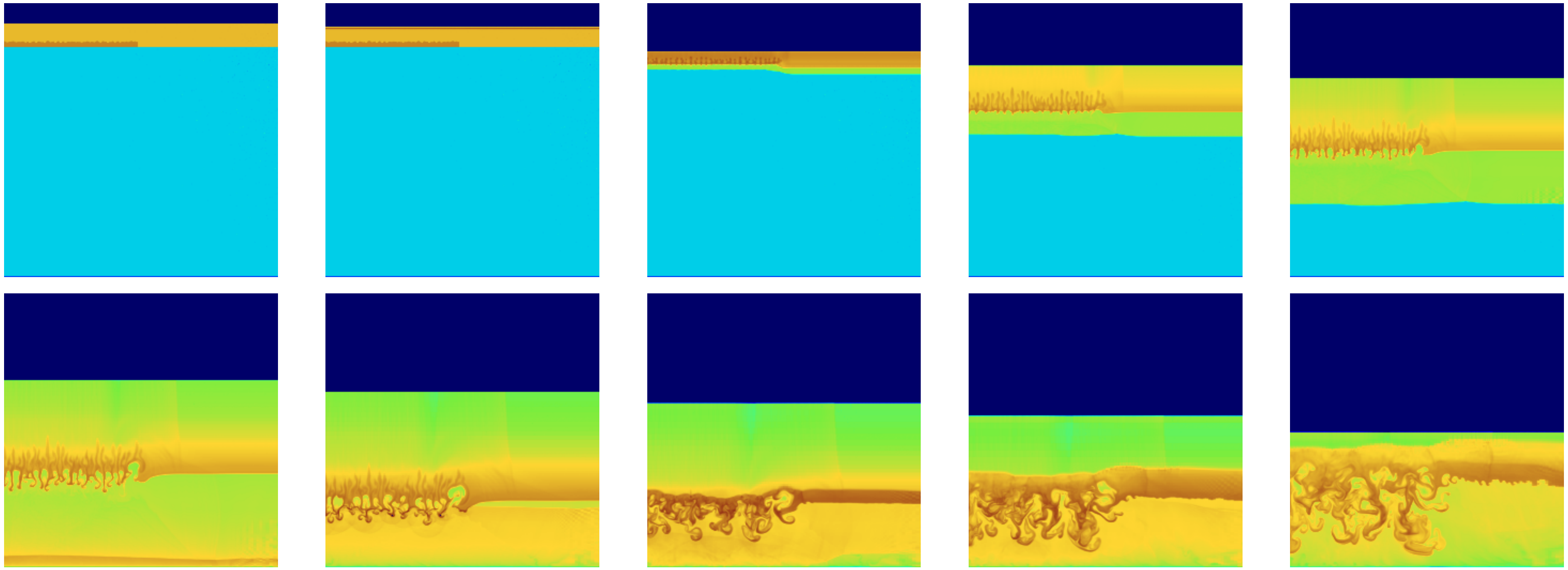


Eagle nebula columns

Astrophysical multiphase flows

Photoionized clumps in the Helix nebula

Experimental multiphase flows



Reshock of Richtmyer-Meshkov fingers, e.g. in cylinder mix experiments.

Some previous numerical studies

- Isolated clumps
  2D Picone & Boris '88; Cowperthwaite '89; Klein et al '94
  3D Stone & Norman '92; Robey et al '02
- MHD: Mac Low et al '94
- Small clusters: Jun et al '96; Steffen et al '97; Hazak et al '98; Poludnenko, Frank & Blackman '02; Collins et al '03
- Continuum approximations:
  Mass loading Hartquist et al '86
  Phase drag Youngs; Williams & Dyson '02

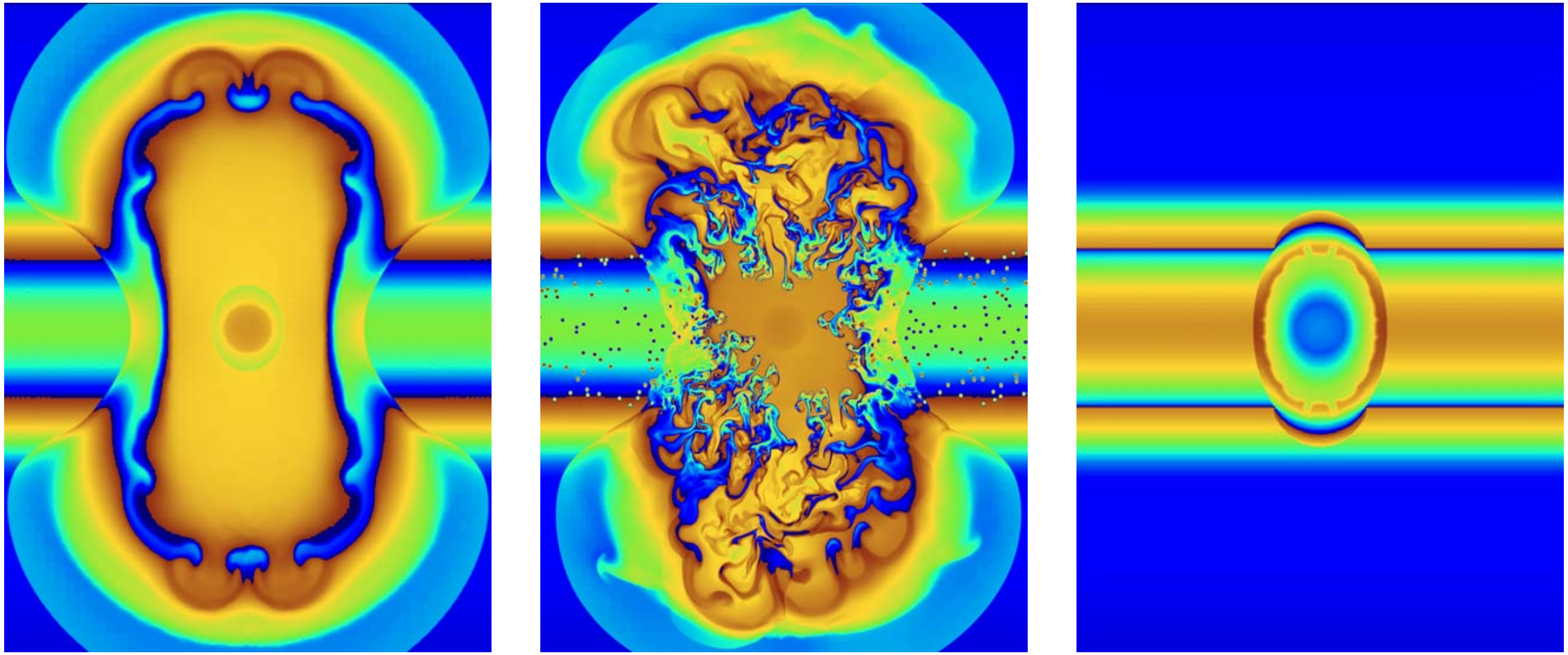
Experimental comparisons

- Shock tube experiments
  - Ranger & Nicholls ’69
  - Haas & Sturtevant ’87
  - Philpott et al ’92
- Laser driven experiments on loaded foam
  - With single sphere (Klein et al ’00; Robey et al ’02)
  - With plastic threads (Frank et al)
  - With dense particles (Foster et al)

Global dynamics

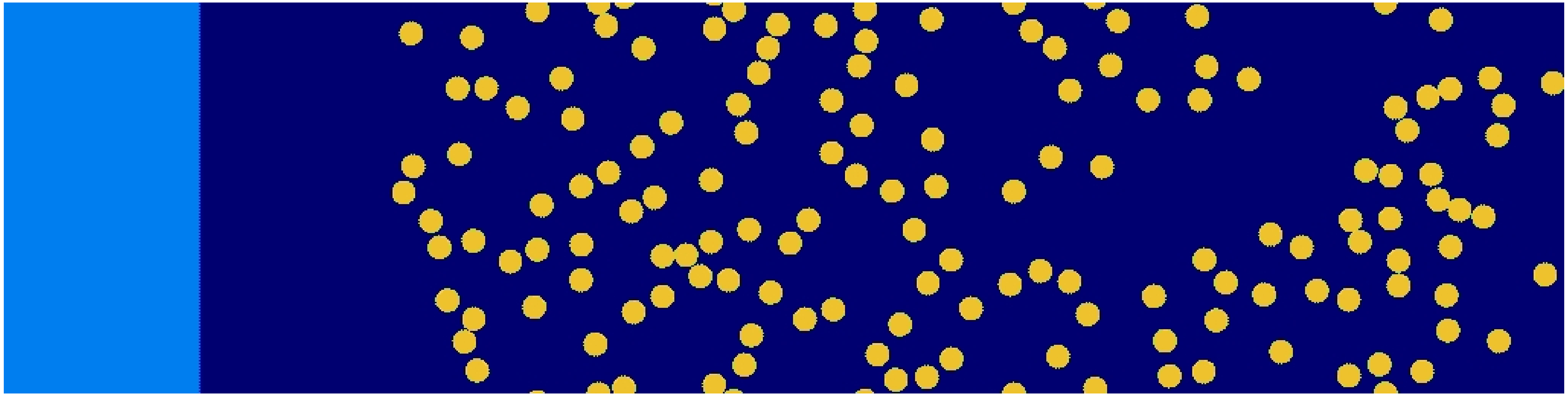
Simplified 2D model of M82

No clouds Explicit Smoothed



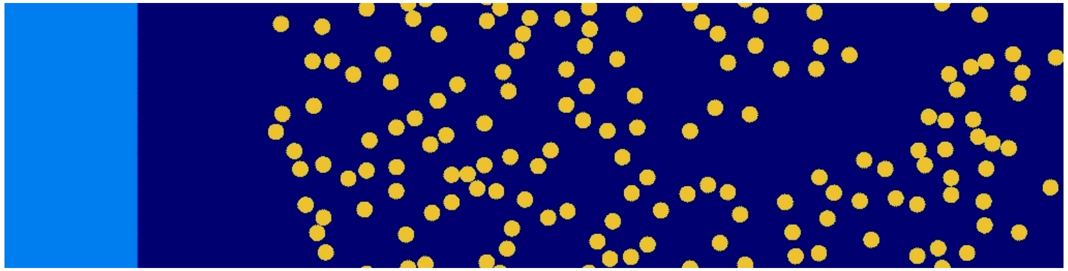
2D AMR simulations

Using Aqualung (Williams '99)

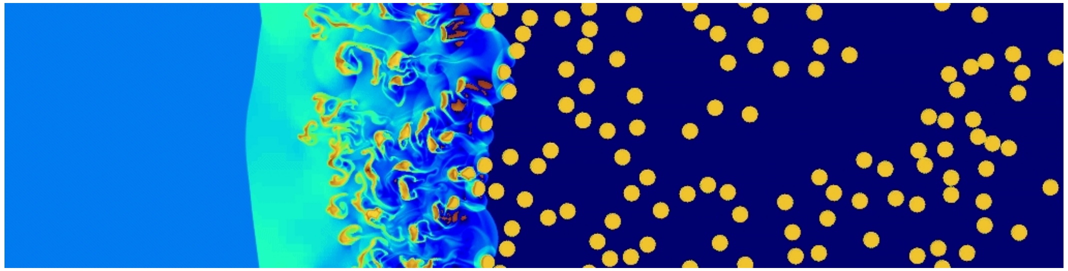


- 150 clumps with density 100× ambient, $\gamma = 5/3$
- effective resolution up to 1024×4096
  - 60 cells across each clump diameter.
- $a = 1$ in upstream diffuse gas, Mach 10 or 2 incident shock.

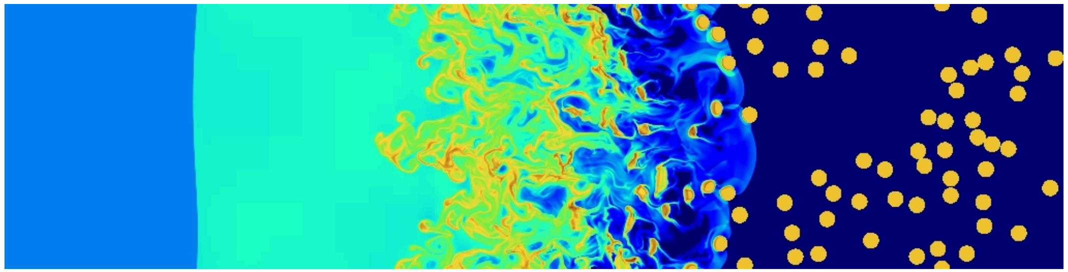
2D AMR simulations – Mach 10



$t = 0$

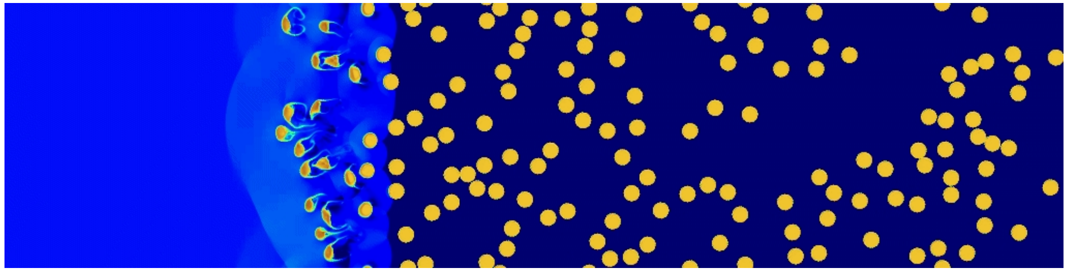


$t = 0.15$

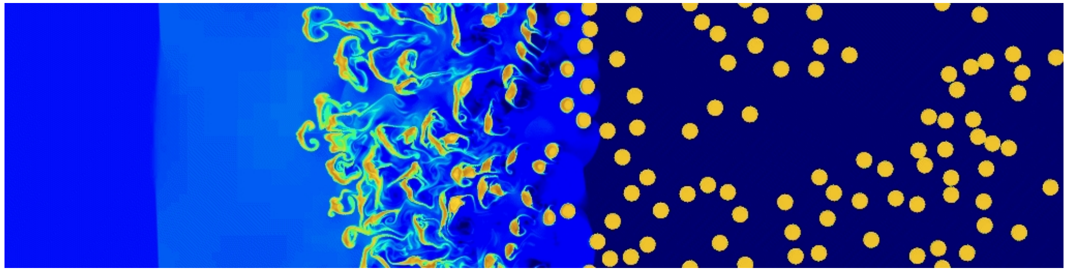


$t = 0.3$

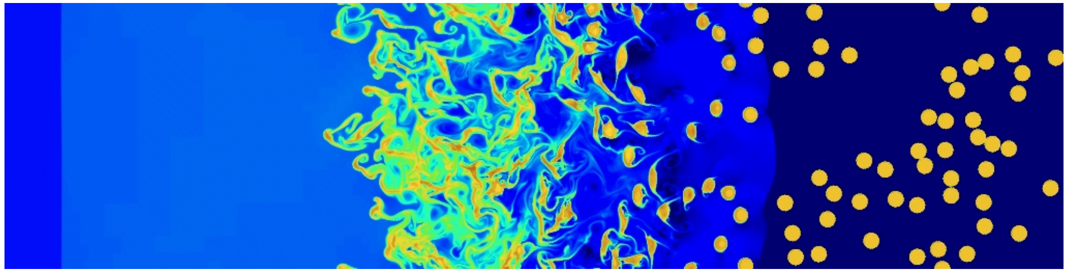
2D AMR simulations – Mach 2



$t = 0.5$

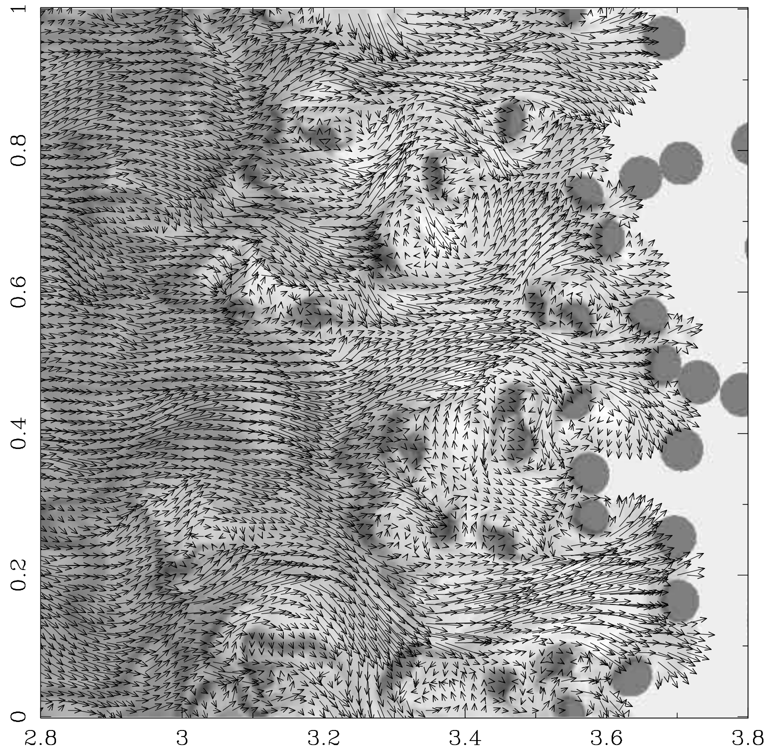


$t = 1.0$



$t = 1.5$

Structure of leading shock in 2D

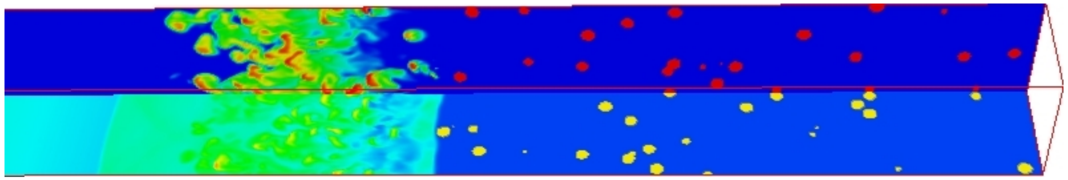


Velocity vector and density for 2D flow, Mach 10 shock.

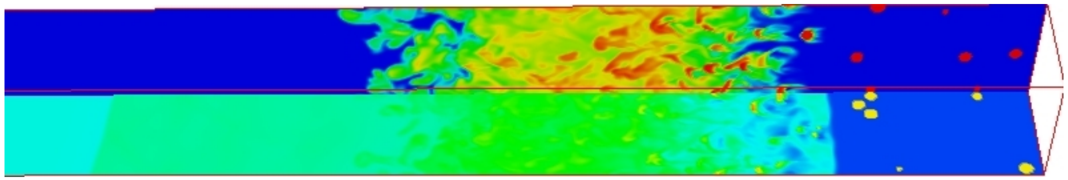
Velocity field highly turbulent, flow nozzles between clumps, compaction at various angles.

3D simulations

Using Turmoil3D (Youngs): mass fraction (upper), density (lower):-

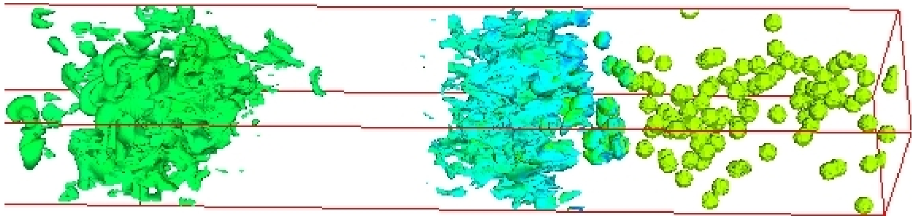


$t = 0.25$



$t = 0.5$

Mass fraction > 0.5 isosurface at $t = 0.5$:-



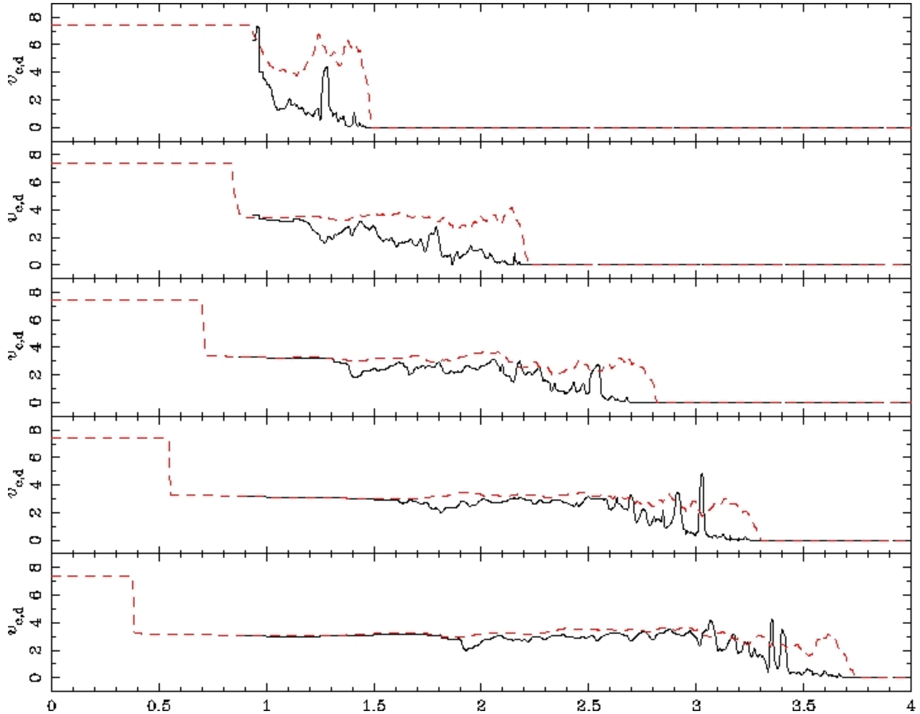
Clump gas is well mixed at this level, surfaces are strongly structured.

3D simulations – II

Column density in 3D simulation – leading shock is closer to plane, initial cloud crushing is more directed.

1D characteristics – Mach 10, 2D

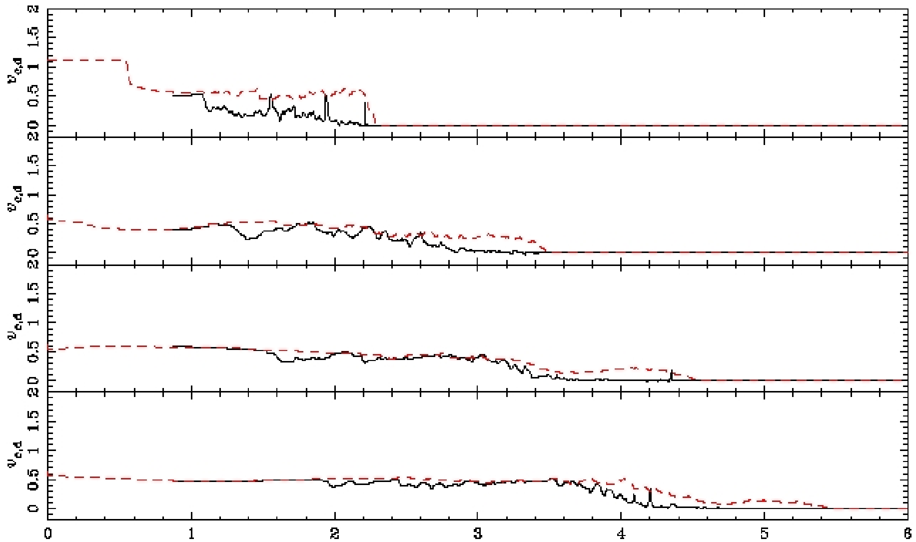
Velocity: clump and diffuse gas, $t = 0.1, ..., 0.5$:-



- Leading diffuse shock weaker, broadened (but still supersonic)
- Clumps catch up. Peaks in early scatter are gaps in clump distribution.

1D characteristics – Mach 2, 2D

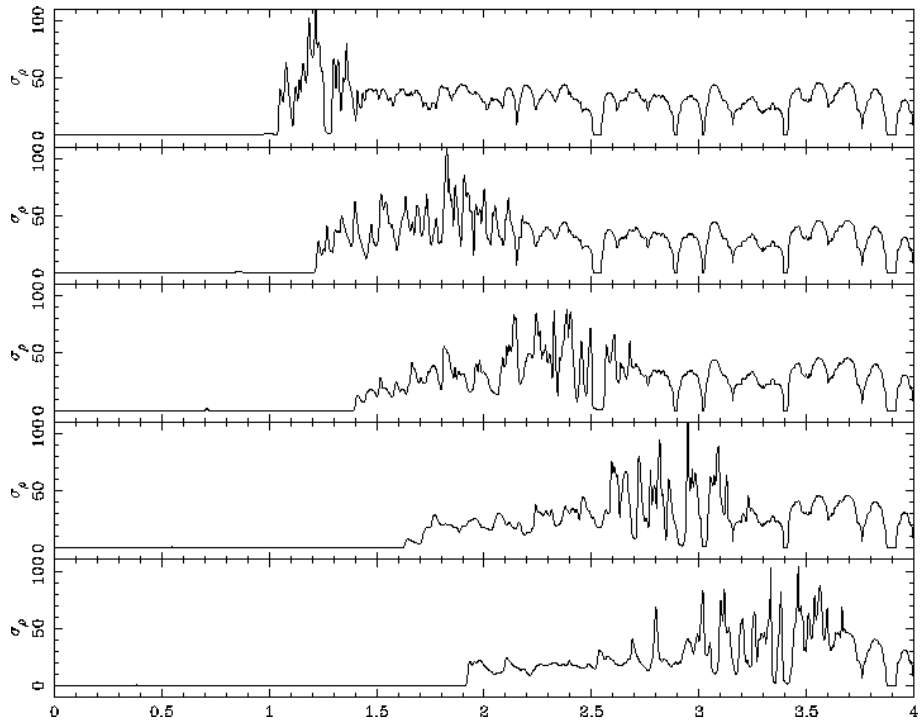
Velocity: clump and diffuse gas, $t = 1, ..., 4$:-



- Leading shock spreads fully
- Precursor wave escapes

1D characteristics – Mach 10, 2D

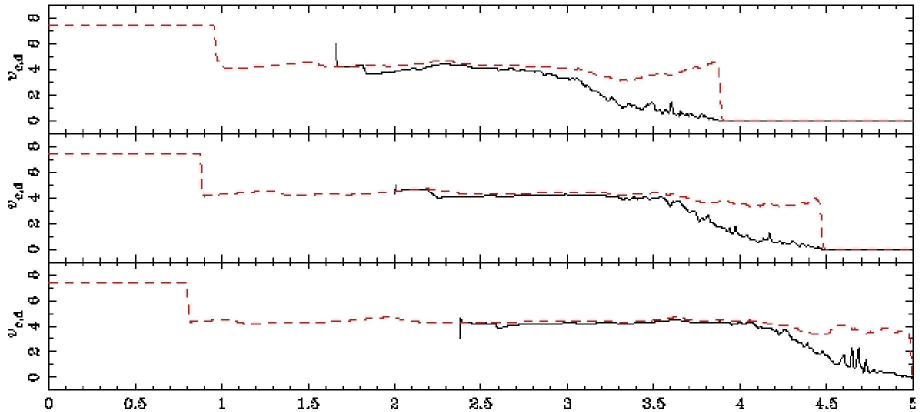
Density RMS:-



Significant density structure remains well after shock passage.

1D characteristics – Mach 10, 3D

Velocity: clump and diffuse gas, $t = 0.4, 0.5, 0.6$:-



- Leading shock in diffuse gas weaker, still sharp
- Clumps catch up in similar distance, with less scatter

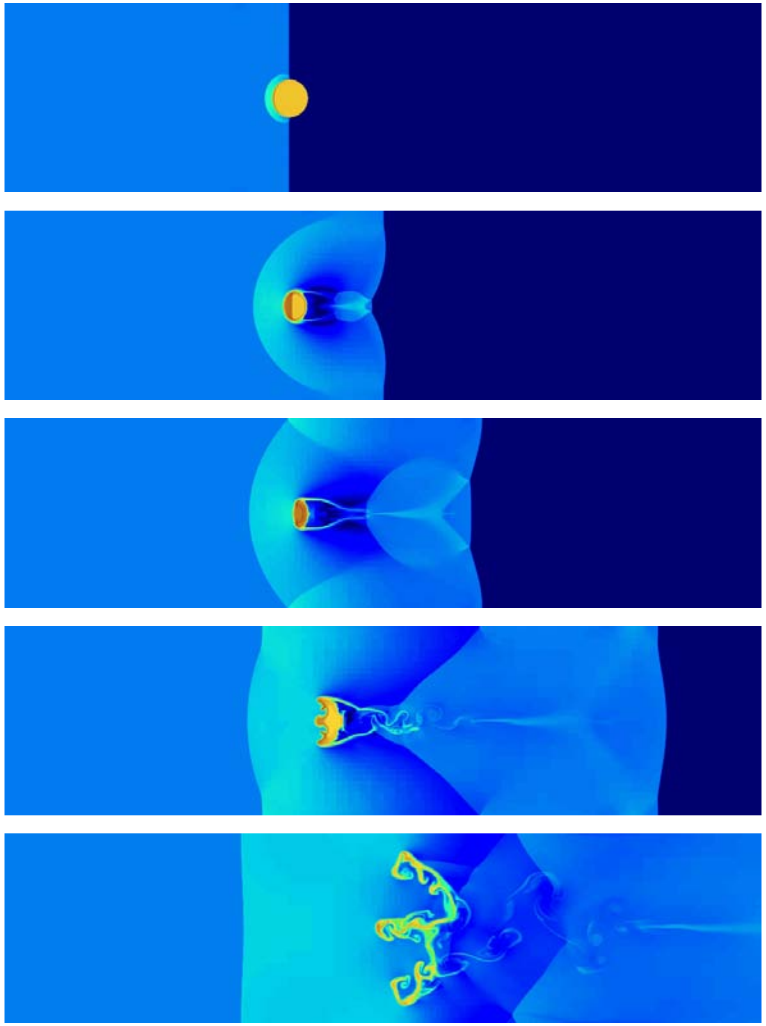
Multiphase flow model

Compare particulate model (adapted from Youngs 1994), with

- Drag
- Added mass terms
- Inter-phase pressure relaxation
- Particle break up

– heat exchange, surface tension/strength and viscosity effects are neglected here.

Developing the multiphase model – I



$t = 0.1$

$t = 0.15$

$t = 0.2$

$t = 0.3$

$t = 0.45$

Developing the multiphase model – II

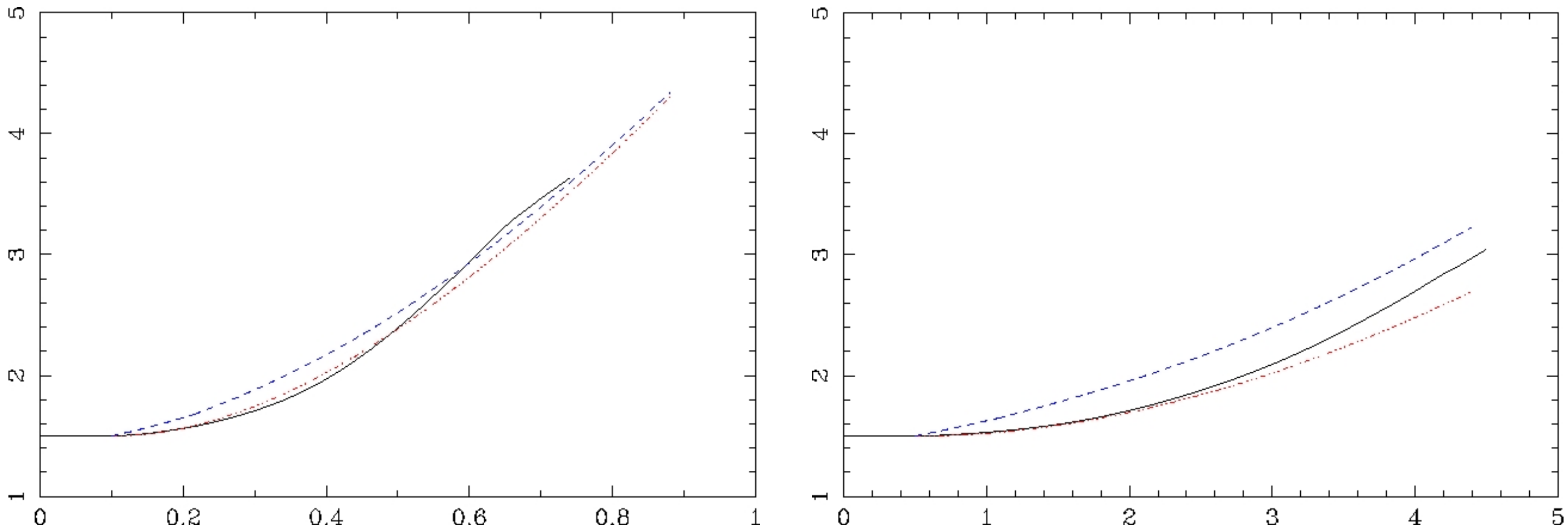
Break up speed from ram pressure balance not sound speed (cf. Poludnenko et al)

Parameters defined using numerical and experimental results.

Gives $v_{\text{rel}} \propto (1 - t/t_{\text{shred}})^{\alpha}$; t_{shred} and α combine break-up and drag.

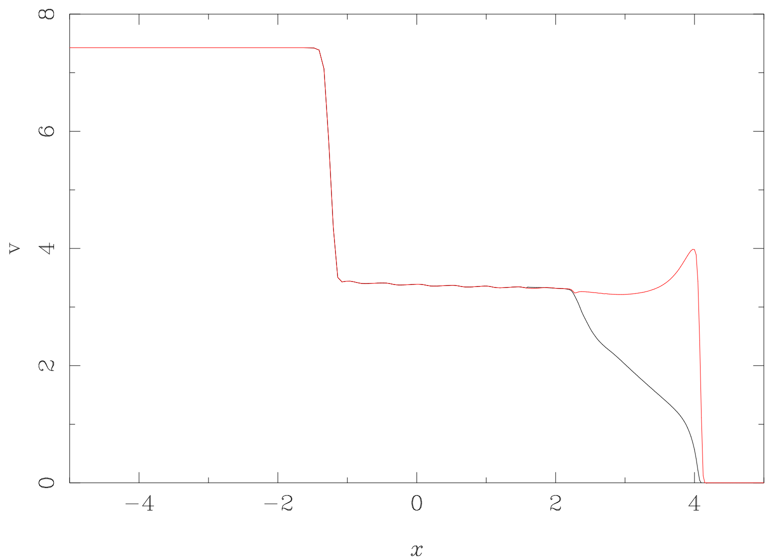
Compare centre of mass motion for single shocked clump.

Mach 10 Mach 2

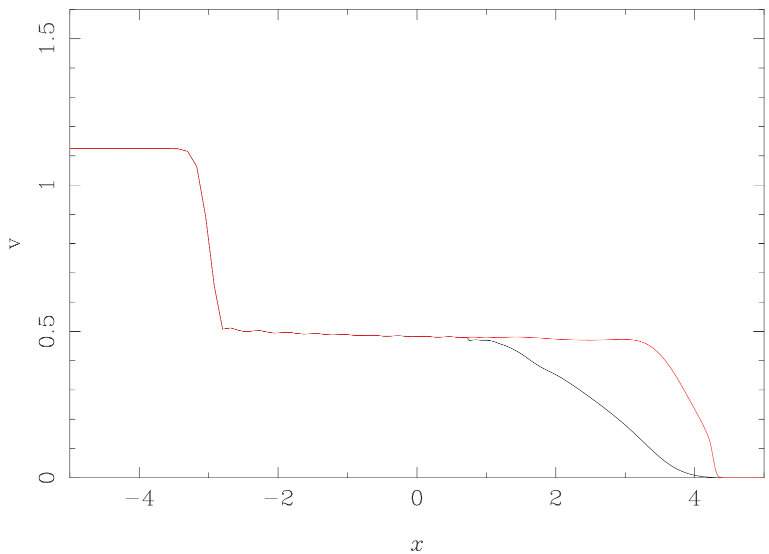


Multiphase flow model results

Mach 10



Mach 2



Velocities of clump and diffuse gas.

Initial particle size reduced to allow for initial anisotropic contraction.

Diffuse overshoot similar to Mach 10 3D results.

Conclusions

- Multiphase structure is common in astrophysics
- Broadens impinging shocks, drives diffuse flows to $\sim$ Mach 1
- Turbulence driven by shock-surface interactions and shock collisions
- Partial mixing occurs, but significant structure remains
- ...so may retain structure with detailed physics (e.g. cooling)
- Experimental comparisons are being developed.