

Supernovae driven Turbulence in the interstellar medium

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May 21, 2010

Supernovae simulations

full 3-D non-ideal MHD, stellar gravity field, differential rotation, radiative cooling

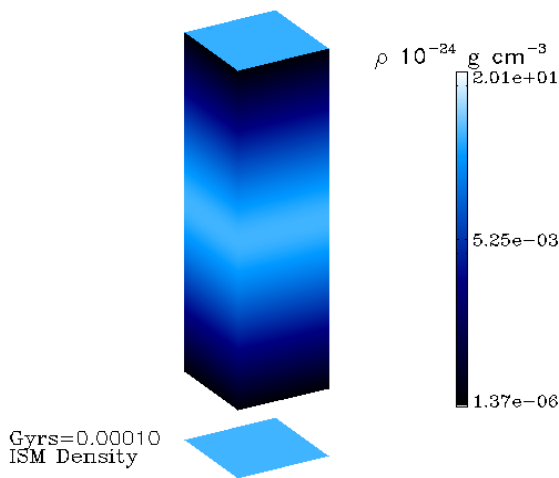


Figure: pencil-code simulation

- ▶ density scale
 $\ln(\rho/10^{-24})$
 10^{-6} to 10
- ▶ mid-plane section
2kpc high by 500pc^2
- ▶ density slices
stellar scale height $\approx 200\text{pc}$
density 1 cm^{-3}
- ▶ time units Gyrs

The equations

- ▶ The continuity equation

$$\frac{\partial \ln \rho}{\partial t} + \mathbf{u} \cdot \nabla \ln \rho = -\nabla \cdot \mathbf{u}$$

- ▶ The equation of state

$$p = \frac{k_B}{\mu m_u} \rho T$$

- ▶ The induction equation

$$\frac{\partial \mathbf{A}}{\partial t} = \mathbf{u} \times \mathbf{B} - \eta \mu_0 \mathbf{j}$$

k_B

Boltzmann constant

m_u

atomic mass

μ

mean molecular weight

η

magnetic diffusivity

μ_0

magnetic permeability

The equations continued

- ▶ The momentum equation

pressure

gravity

Lorentz

shock
viscosity

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -c_s^2 \nabla \left(\frac{s}{c_p} + \ln \rho \right) - \nabla \Phi_{\text{grav}} + \frac{\mathbf{j} \times \mathbf{B}}{\rho} + \zeta (\nabla \nabla \cdot \mathbf{u}) + \nu \left(\nabla^2 \mathbf{u} + \frac{1}{3} \nabla \nabla \cdot \mathbf{u} + 2\mathbf{S} \cdot \nabla \ln \rho \right)$$

- ▶ The entropy equation

SN & UV
heating

radiative
cooling

Ohmic
heating

$$\rho T \left(\frac{\partial s}{\partial t} \right) + \mathbf{u} \cdot \nabla s = \mathcal{H} - \mathcal{C} + \nabla \cdot (K \nabla T) + \eta \mu_0 \mathbf{j}^2 + 2\rho \nu \mathbf{S}^2 + \zeta \rho (\nabla \cdot \mathbf{u})$$

The model

- ▶ shearing box - differential rotation
radial/azimuthal - periodic/sliding
- ▶ gravity profile (?)

$$g_z = \frac{g_\alpha z}{\sqrt{z^2 + 200\text{pc}^2}} + \frac{g_\beta z}{1\text{kpc}^2}$$

- ▶ $t=0$: isothermal hydrostatic equilibrium

$$\rho(z) = \rho_0 \exp\left(\frac{0.4g_\alpha - 2g_\alpha \sqrt{z^2 + 0.2^2} - g_\beta z^2}{2\tau_0}\right)$$

$$\rho(z) \propto \rho(z), T(0) = 8000\text{K}$$

- ▶ radiative cooling, uv heating, seed magnetic field $10^{-2}\mu\text{G}$

Supernovae model

- ▶ Type I & Type II SNe:
 - ▶ inject 10^{51} ergs (thermal & kinetic energy) & mass $4M_{\odot}$
 $24 \text{ Myrs}^{-1} \text{ kpc}^{-2}$
 - ▶ SNI: random uniform in x,y; gaussian in z to height 350 pc
 - ▶ SNI: Poisson time process, dependent on cloud mass
 $T < 4000\text{K}$ and $\rho > 1$, random site, bias for most dense cloud
- ▶ Sedov and snowplough growth reproduced

$$R = \left(\frac{25}{3\pi} \right)^{\frac{1}{5}} \left(\frac{E}{\rho_0} \right)^{\frac{1}{5}} t^{\frac{2}{5}} \quad (\text{adiabatic})$$

$$R = R_0 \left(1 + 4 \frac{\dot{R}_0}{R_0} (t - t_0) \right)^{\frac{1}{4}} \quad (\text{snowplough})$$

- ▶ transition velocity \dot{R}_0 between two phases

$$\dot{R}_0 \propto \rho_0^{2/17} E^{1/17} \quad (?)$$

Effect of initial remnant radius on expansion

single SN approximated with energy injected into finite sphere

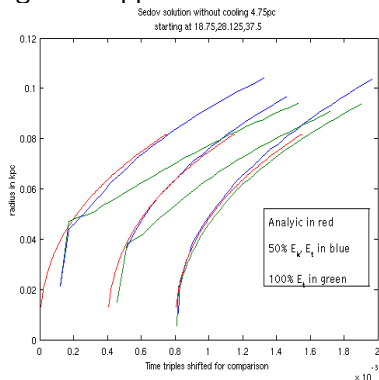


Figure: Adiabatic growth of SN remnant shell mixed thermal/kinetic, only thermal and analytic for various initial remnant sizes

- ▶ Why increase remnant size?
- ▶ Injection of thermal energy only:
 10^{51} ergs at rest
- ▶ Injection of joint kinetic-thermal energy:
 5×10^{50} ergs thermal plus equivalent velocity

Single supernova

Comparison to Sedov solution with larger initial remnant size

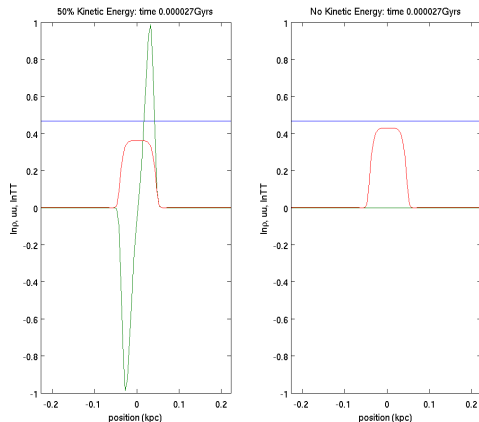


Figure: Single SN simulation without cooling: 1-D section through the remnant origin **density**, **shock velocity** and **temperature**

- ▶ no radiative cooling
- ▶ injected thermal/kinetic energy
good match to Sedov
reverse shock - high temp
- ▶ injected thermal energy only
stable but too slow

Single SN remnant with radiative cooling function

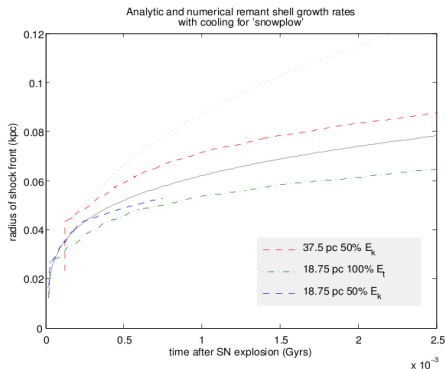


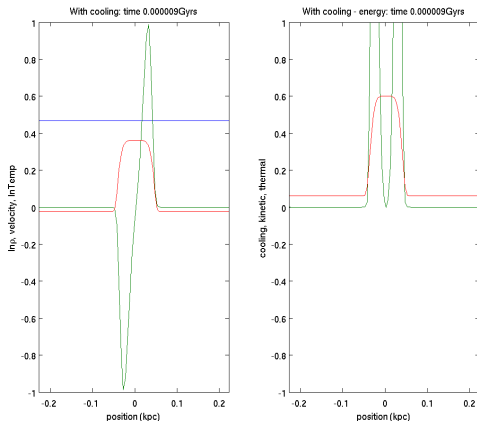
Figure: Comparing simulations with radiative cooling to snowplow

- ▶ solid line - snowplow
- ▶ Initial remnant 37.5pc thermal-kinetic energy
- ▶ Initial remnant 18.75pc thermal energy only
- ▶ Initial remnant 18.75pc thermal-kinetic energy
too hot for code
- ▶ Initial remnant 37.5pc thermal energy only
too cold for growth

Single SN remnant

$$\rho \quad T \quad V_r$$

$$\Lambda(T) \quad E_T \quad E_K$$



- ▶ density, radial velocity and temperature
- ▶ cooling, kinetic energy and thermal energy
- ▶ Hot & warm phases
 $\approx 8000\text{K}$ & $> 10^6\text{K}$

Figure: thermal-kinetic energy in initial 37.5pc remnant with cooling: 1D-sections through the origin

Radiative cooling

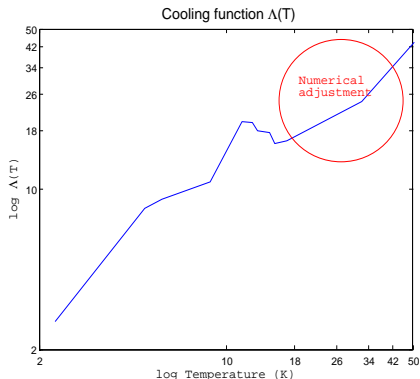


Figure: Radiative cooling function includes unphysical cooling above 10^7 K to inhibit unresolvable hot gas.

- ▶ Continuous cooling function
(?)
(?)
- ▶ uv-heating constant smoothly vanishes above 8000K
(?)
- ▶ Is high end truncation justified?

Preliminary results: hydrostatic model

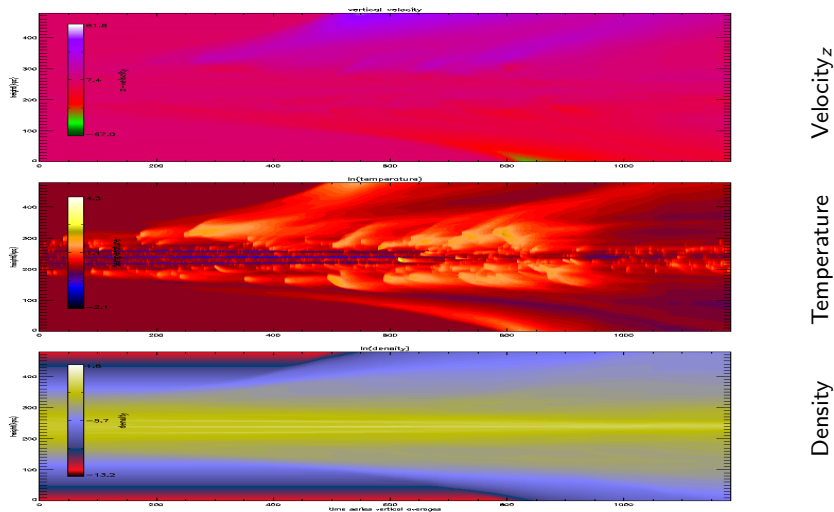


Figure: Time series of vertical averages for vertical velocity, log(temperature) & log(density)

Mean velocity temperature and supernova rate

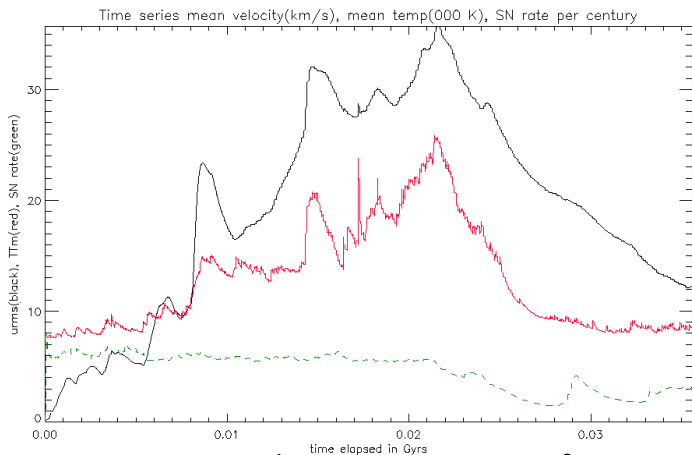
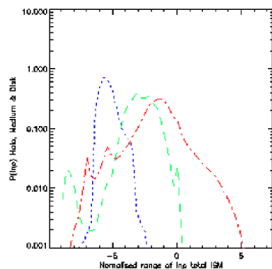


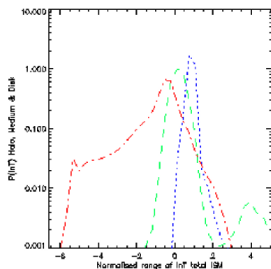
Figure: Mean velocity (km s^{-1}), mean temperature (10^3 K) and supernovae events per century.

Probability density - by height

Density



Temperature



Velocity

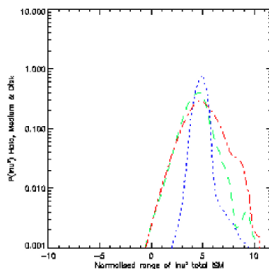


Figure: Probability density plots at 58 Myrs for $\log(\text{density})$, $\log(\text{temperature})$ and $\log(\text{velocity}^2)$ in the **halo**, **mid-height** and **disk**

Volume filling factors heat phases

volume filling factors at 44 Myrs

| | $T \leq 200 \text{ K}$ | $200 \text{ K} < T \leq 10^4 \text{ K}$ | $T > 10^4 \text{ K}$ |
|--------------------------|------------------------|---|----------------------|
| $< 200 \text{ pc}$ | 0.049 | 0.764 | 0.187 |
| $< 500 \text{ pc}$ | 0 | 0.126 | 0.867 |
| $\geq 500 \text{ pc}$ | 0 | 0 | 0.994 |
| Total $\leq 1\text{kpc}$ | 0.015 | 0.191 | 0.794 |

volume filling factors at 58 Myrs

| | $T \leq 200 \text{ K}$ | $200 \text{ K} < T \leq 10^4 \text{ K}$ | $T > 10^4 \text{ K}$ |
|--------------------------|------------------------|---|----------------------|
| $< 200 \text{ pc}$ | 0.042 | 0.789 | 0.170 |
| $< 500 \text{ pc}$ | 0 | 0.302 | 0.692 |
| $\geq 500 \text{ pc}$ | 0 | 0 | 0.993 |
| Total $\leq 1\text{kpc}$ | 0.013 | 0.249 | 0.738 |

Temperature of supernovae simulations

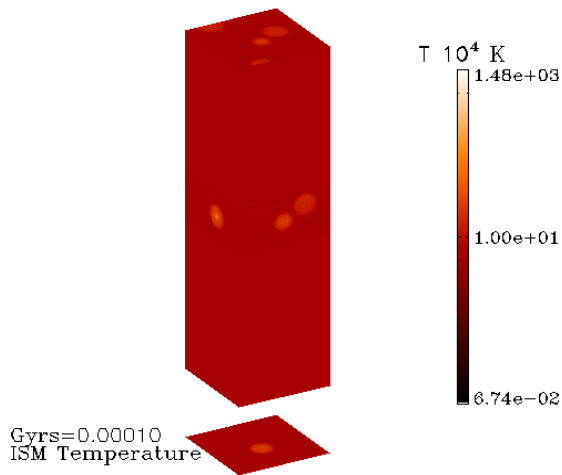
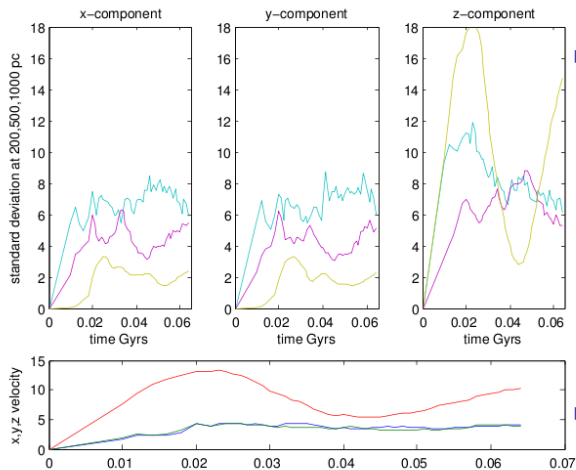


Figure: hydrostatic simulation showing temperature

- ▶ temperature scale $\ln(T10^4)$ K
 10^{-4} to 10^3
- ▶ mid-plane section
2kpc high by 500 pc²
- ▶ temperature slices
- ▶ mean ISM temperature
8000 K
- ▶ time units Gyrs

Anisotropy of velocity fluctuations



▶ velocity variance comparison by height:

< 200,

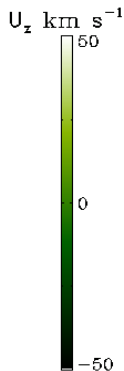
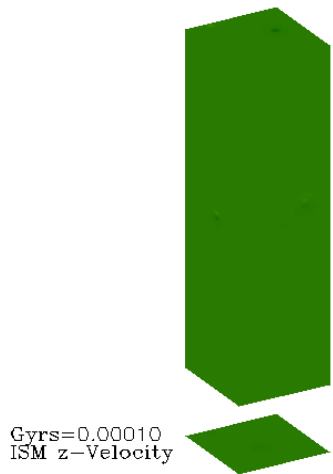
200 – 500,

500 – 1000pc

▶ velocity variance in total volume by V_x, V_y, V_z

Figure: Standard deviation from mean velocity for V_x, V_y, V_z < 200pc, 200 to 500pc & 500pc to 1kpc. Plus V_x, V_y, V_z fluctuations for whole volume (V_z in red)

Vertical velocity of supernovae simulations



- ▶ velocity scale (km s^{-1})
- ▶ mid-plane section
2kpc high by 500 pc²
- ▶ z-velocity slices
- ▶ mean ISM velocity 10-15 km s^{-1}
- ▶ time units Gyrs

Figure: hydrostatic simulation showing vertical velocity flow

Flow through the vertical boundaries

Fountain or wind?

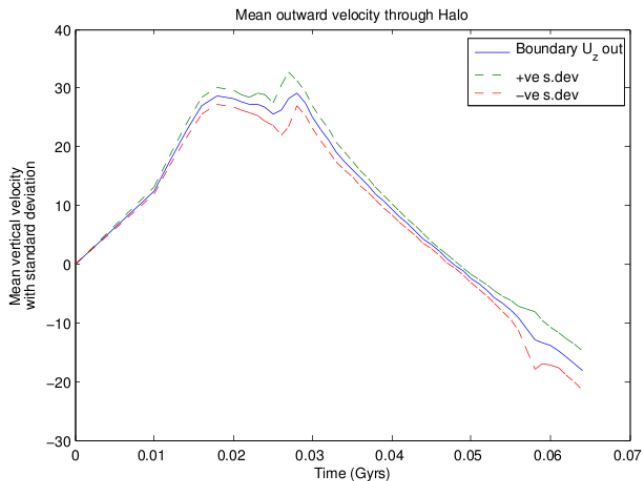
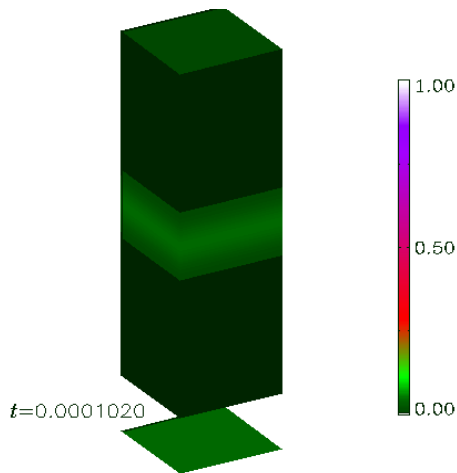


Figure: Mean outward velocity on vertical boundaries ± 1 kpc

Further development and investigation

Results still very preliminary. Code under revision.



- ▶ include cosmic rays
- ▶ larger box to study dynamo
- ▶ investigate parameter space
- ▶ suggestions for further testing and improvements

Figure: Magnetic field B^2 scale 0 to $0.345591 \mu\text{G}$