Supernovae driven Turbulence in the interstellar medium

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March 4, 2010

Supernovae simulations

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

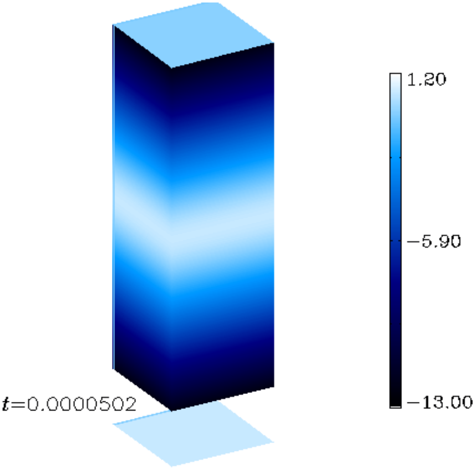


Figure: pencil-code simulation

- density scale $\ln(\rho/10^{-24})$ -13 to 1.2
- mid-plane section

  2kpc high by 500pc^2
- density slices

  stellar scale height $\approx$ 200pc

  density 1 cm^{-2}
- time units Gyrs

The model

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

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

- t=0: isothermal hydrostatic equilibrium

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

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

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

Supernovae model

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

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

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

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

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

Effect of initial remnant radius on expansion

single SN approximated with energy injected into finite sphere

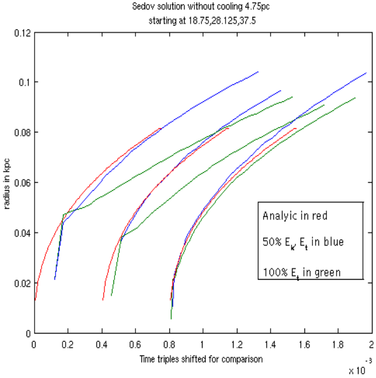


Figure: Adiabatic growth of SN remnant shell mixed thermal/kinetic, only thermal and analytic for various initial remnant sizes

- 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

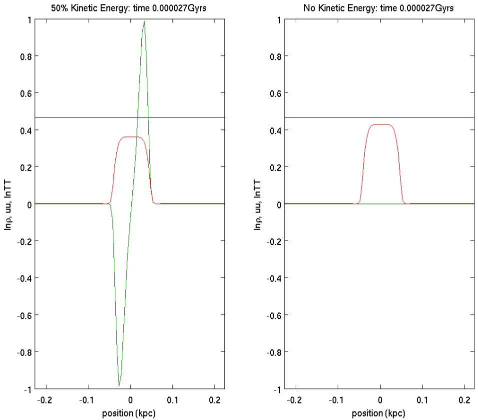


Figure: Single SN simulation without cooling: 1-D section through the remnant origin density, shock velocity and temperature

- 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

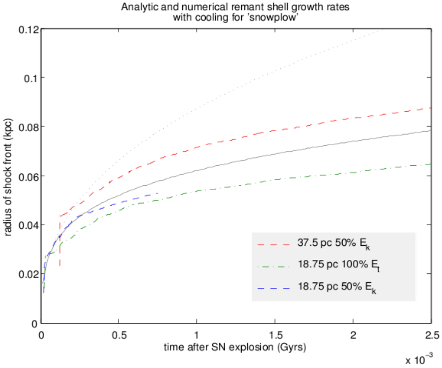


Figure: Comparing simulations with radiative cooling to snowplough

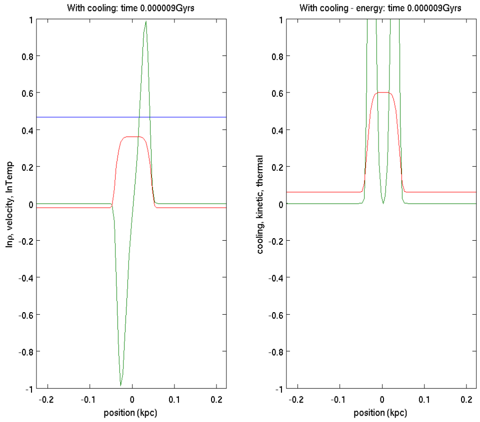
- solid line - snowplough
- Initial remnant 37.5pc thermal-kenetic energy
- Initial remnant 18.75pc thermal energy only
- Initial remnant 18.75pc thermal-kinetic energy

  too hot for code
- Initial remnant 37.5pc thermal energy only

  too cold for growth

Single SN remnant

ρ T V_r $\Lambda(T)$ E_T E_K



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

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

Radiative cooling

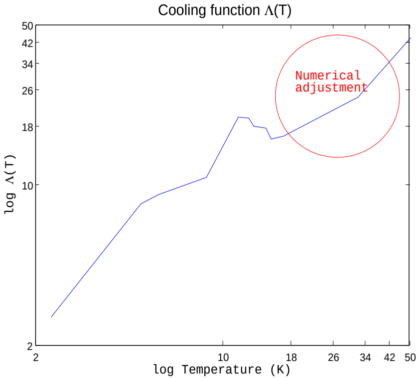


Figure: Radiative cooling function includes unphysical cooling above 10^7K to inhibit unresolvable hot gas.

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

Probability density - by height

Density Temperature Velocity

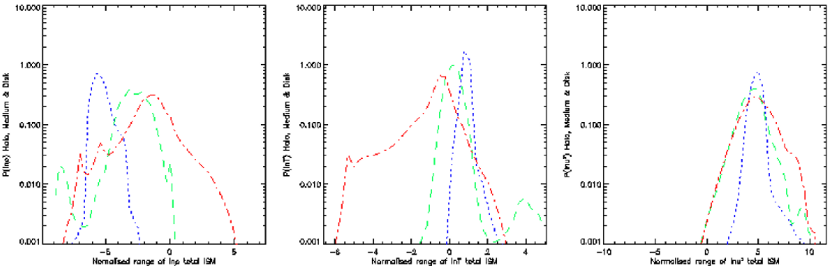


Figure: Probability density plots at 58 Myrs for log(density),log(temperature) and log(velocity^2) in the halo, mid-height and disk

Volume filling factors heat phases

volume filling factors at 44 Myrs

	$T \leq 200$ K	200 K $< T \leq 10^4$ K	$T > 10^4$ K
< 200 pc	0.049	0.764	0.187
< 500 pc	0	0.126	0.867
≥ 500 pc	0	0	0.994
Total $\leq$ 1kpc	0.015	0.191	0.794

volume filling factors at 58 Myrs

	$T \leq 200$ K	200 K $< T \leq 10^4$ K	$T > 10^4$ K
< 200 pc	0.042	0.789	0.170
< 500 pc	0	0.302	0.692
≥ 500 pc	0	0	0.993
Total $\leq$ 1kpc	0.013	0.249	0.738

Average Velocity and Magnetic fluctuations

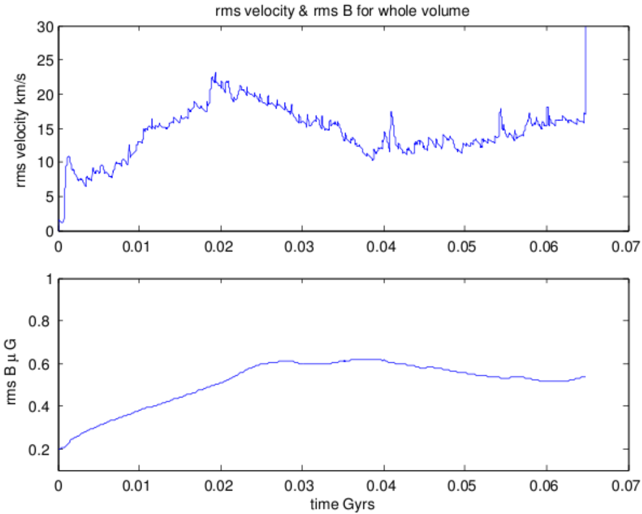


Figure: Mean velocity and magnetic field strength in the whole volume. Seed field grows from 0.05μG to about 0.5μG

Anisotropy of velocity fluctuations

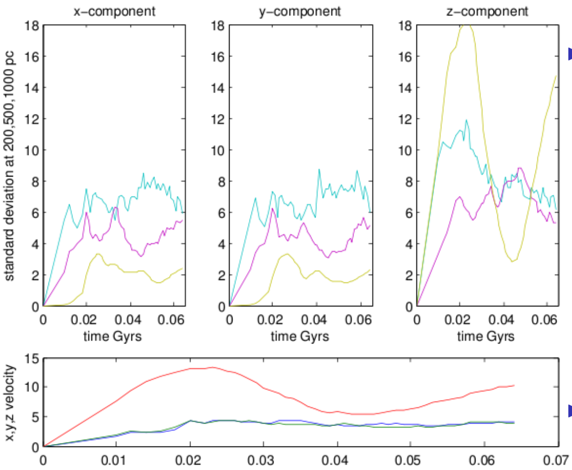


Figure: Standard deviation from mean velocity for V_x, V_y, V_z < 200pc, 200 to 500pc & 500pc to 1kpc. Plus V_x, V_y, V_z fluctuations for whole volume (V_z in red)

- velocity variance comparison by height: < 200, $200 - 500$, $500 - 1000$pc
- velocity variance in total volume by V_x, V_y, V_z

Flow through the vertical boundaries

Fountain or wind?

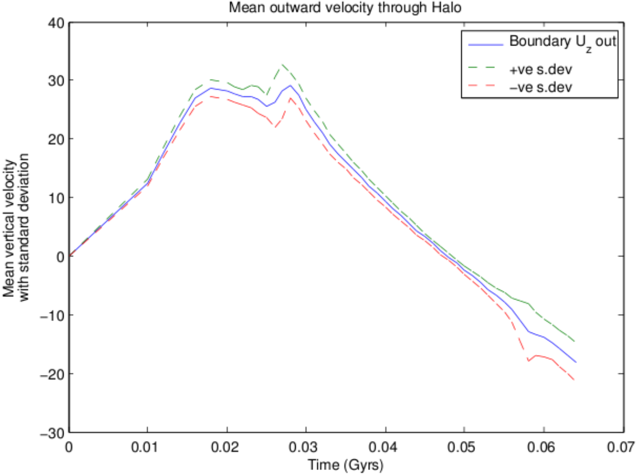


Figure: Mean outward velocity on vertical boundaries ± 1 kpc

Further development and investigation

Results still very preliminary. Code under revision.

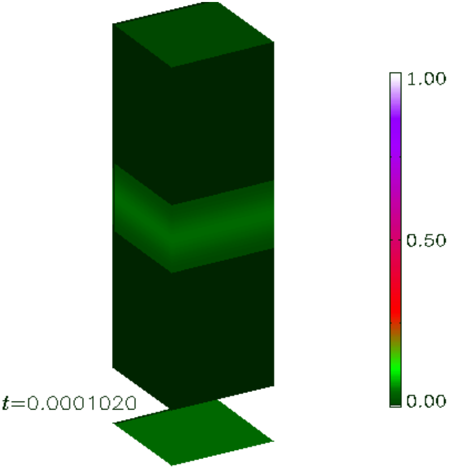


Figure: Magnetic field B^2 scale 0 to 0.345591 μG

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