Outlines

• 2D simulations of matter mixing in supernovae

• 3D MHD simulation of a supernova remnant
Matter mixing in supernovae
Propagation of supernova shock wave

- Radial velocity
- Mixing of heavy elements into high velocity regions?

Synthesized heavy nuclei such as $^{56}\text{Ni}$

- $^{56}\text{Ni}$ ($^{56}\text{Co}$)
- He/H

Questions:
- $^{56}\text{Ni}$ ($^{56}\text{Co}$)
- Radial velocity
- Shock Wave

C+O/He He/H Surface
Observational evidences of mixing in supernovae

• SN1987A
  – Early detection of X-rays (Dotani et al. 1987), γ-rays lines (Matz et al. 1988)
  – Line profiles of [Fe II] (Spyromilo+90; Haas+90)

Iron (\(^{56}\)Ni) is mixed into high velocity regions?
Broadened line profiles of SN1987A

[Fe II] line profiles (Spyromilo+90; Haas+90)

Iron is mixed into high velocity regions?

Haas et al. 1990
Previous studies of mixing in SNe

- Rayleigh-Taylor (RT) mixing at O/He, He/H interfaces
- 2D/3D hydrodynamic simulations, 2D/3D SPH
- Add hoc models of supernova explosion
  - Thermal bomb, piston model
- Maximum $^{56}\text{Ni}$ velocity around 2,000 km s$^{-1}$
- Large initial amplitude of perturbation $\sim$ a few 10% is required to explain observations in some papers

2D simulations of non-spherical neutrino-driven supernova explosions

Kifonidis et al. 2006; Gawryszczak et al. 2010

- Neutrino heating model aided by SASI
  - Global asphericity at the explosion
- $2 \times 10^{51}$ erg

Solid circle : $10^{-4} \, M_{\odot}$
Open circle : $10^{-5} \, M_{\odot}$
Motivation

• Rayleigh-Taylor instability itself is not enough to explain high velocity of $^{56}$Ni?

• Effects of the mildly aspherical supernova shock on the growth of RT instabilities

Revisiting RT instabilities in supernovae from explosion to around shock breakout
FLASH Code

The FLASH code is a modular, parallel multiphysics simulation code capable of handling general compressible flow problems found in many astrophysical environment (Fryxell et al. 2000)

• Eulerian hydrodynamic code
  – Piecewise Parabolic Method (PPM)
  – Unsplit solver, MHD, RHD
• AMR (Adaptive mesh refinement)
  – Reduce numerical costs
• Many optional units
  – Nuclear reaction networks (7-19 nuclei)

Type Ia SN explosion

Jordan et al. 2008
Initiation of explosions

\[ E_{\text{kin}} = E_{\text{kin}} + E_{\text{thermal}} \]

\[ E_{\text{kin}} : E_{\text{thermal}} = 1 : 1 \]

\[ v_r \propto \frac{r(1 + \alpha \cos(2\theta))}{1 + \alpha} \]

\[ \frac{v_{\text{pol}}}{v_{\text{eq}}} = \frac{1 + \alpha}{1 - \alpha} \]
Possible RT unstable regions

$6\, M_\odot$ helium core + hydrogen envelope (Nomoto & Hashimoto 1988)

\[ \rho \, r^3 \uparrow \]
\[ \rightarrow \text{ decelerate} \]

\[ \nabla \rho \cdot \nabla p < 0 \]
Perturbation

- Random
  \[
  v_r = v_{r,0}(1 + \epsilon(2 \text{ rand } [m \theta / \pi] - 1))
  \]

- Sinusoidal
  \[
  v_r = v_{r,0}(1 + \epsilon \cos(m \theta / \pi))
  \]

- Position that the perturbations are inputted
  - \(3 \times 10^8\) cm (Si/C+O), \(5 \times 10^{10}\) cm (H/He)

- Amplitude : \(\pm 5\%\)
Minxing in SNe
Mixing length

Sin. inner       Random. outer       Sin. outer
Mass fraction of elements: random perturbation case

$^{56}\text{Ni}$

$^{16}\text{O}$
Mass fraction of elements: sinusoidal perturbation case

56Ni

16O
Radial velocity distributions

Random, inner

Random, outer
Line of sight velocity distributions

Random, outer

[Fe II] 1987A
Haas et al. 1990
Short summary

- Even if the supernova shock is aspherical, most of the $^{56}\text{Ni}$ have $< 1000$ km s$^{-1}$

- Mixing length of RT depends on the position that perturbations are inputted and shape of the perturbation (random/sinusoidal)

- RT growth in He/(C+O) ?
3D MHD simulation of a SNR
Introduction

• Acceleration of cosmic-ray in SNRs
  – Up to $10^{15}$ eV or more?
  – Magnetic field is key ingredient

SN1006 (Chandra: X-ray)
Amplified strong magnetic field?

Uchiyama et al. 2007, Nature, 4469 576

Variations of X-ray hot spots on a 1 yr timescale

Strong amplified magnetic field?

Bohm-diffusion limit

\[ t_{\text{synch}} \approx 1.5 \left( \frac{B}{\text{mG}} \right)^{-1.5} \left( \frac{\epsilon}{\text{keV}} \right)^{-0.5} \text{ yr} \]

\[ t_{\text{acc}} \approx 1 \eta \left( \frac{\epsilon}{\text{keV}} \right)^{0.5} \left( \frac{B}{\text{mG}} \right)^{-1.5} \left( \frac{v_s}{3,000 \text{ km s}^{-1}} \right)^{-2} \text{ yr} \]
Role of ejecta clumping

- Small separation between the FS and CD (SN1006: Miceli et al. 2009) can be explained by ejecta clumping

Orlando et al. 2011
Initial clumpy ejecta for a Type Ia SN

Exponential ejecta profile for Type Ia SNRs
Dwarkadas & Chevalier 1998

$$\rho_{SN} = A \exp(-v/v_{ej}) t^{-3}$$

$$v_{ej} = \left( \frac{E_{\text{kin}}}{6 M_{ej}} \right)^{1/2} \quad v = r/t$$

$$A = \frac{6^{3/2} M_{ej}^{5/2}}{8 \pi E^{3/2}}$$

$$P = \kappa \rho^{4/3}$$

Wang 2005

$$E_{\text{kin}}: \text{kinetic energy} \ (10^{51} \text{ erg})$$
$$M_{ej}: \text{ejecta mass} \ (1.37 \, M_\odot)$$

B = 1 \, \mu G

0.5 pc
Volume rendering images of density

Volume rendering images of density

3 pc
Amplified magnetic field

1 μG

~ 50 μG
Summary

• RT instability due to the clumpy ejecta can explain the small distance between FS and CD (Orlando+11)

• Magnetic field can be amplified by kind of turbulence motion of clumpy ejecta via RT instabilities (Orlando+11)