Explosion Mechanism of Core-collapse Supernovae

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Theory

Observation

Simulation

```
module commons
implicit NONE

real*8 :: real8
integer, parameter :: rl = kind(real8)

parameter

  real*8  pi, tiny, huge
  parameter(pi = 3.14159 26535 89793 23846d0)
  parameter(tiny = 1.0000e-30 )
  parameter(huge = 1.0000e+30 )
character(2):: id
integer :: incr
integer:: strtei
logical flag

units

  real(rl), parameter :: M_0 = 1.4d0*1.989d33
```

\[ e^{-} \rightarrow \gamma \rightarrow e^{+} \]

\[ e^{-} \rightarrow g \rightarrow q \rightarrow t \]
Era of 3D simulations is coming for neutrino driven explosion

![3D Simulations](image)
Contents

• Basics of $\nu$-heating mechanism

• 3D no-rotating model
  explosive nucleosynthesis

• 1D artificial exploding model
  (long term simulation)
  r-process nucleosynthesis?

• 3D rotating model
  r-process nucleosynthesis?

• Toward making convincing

• Summary
Two class of CC SNe

Neutrino Mechanism

Magnetic Mechanism

We focus on this

Rotation

Magnetic Fields

Rotation

pulsar

magnetar

BH

Talk by Nishimura
Basic setup

Density

Velocity

Entropy (~T^3/ρ)

Radius [km]

(1) Gravitational Collapse
(2) Core-bounce by nuclear force
(3) Shock propagation and stalling

Radius [km]
Key aspects of Neutrino Mechanism

Radial Velocity

When the shock is stalling, Pressure inside and ram pressure outside balances.

\[ p \sim \rho \Delta v^2 \]

RHS is determined by stellar structure (density profile).

LHS is determined by two ingredients.

1. Photo-dissociation

\[ \text{Fe} \rightarrow 30\text{n} + 26\text{p} - \Delta Q \]

2. Neutrino Heating

\[ \nu_e + \text{n} \rightarrow \text{e}^- + \text{p} + \Delta Q \]

\[ \bar{\nu}_e + \text{p} \rightarrow \text{e}^+ + \text{n} + \Delta Q \]
Problem

Supernovae shock in simulation tend to stall and does NOT explode.


Why does SN in real world explode?
Why does SN in sim. fail to explode?
Contents

• Introduction
• 3D no-rotating model explosive nucleosynthesis
• 1D artificial exploding model r-process nucleosynthesis?
• 3D rotating model r-process nucleosynthesis?
• Toward making convincing
• Summary
Most distinct development is shift from 1D to 3D (or 2D)!

We succeed to make a few explosion model!
Key aspects of Neutrino Mechanism

Entropy $\sim T^3/\rho$

- Convective energy transport
- $\nu$ reaction: $\text{Fe} \rightarrow n, p$
- Heated by neutrino
- Cooling by photodissociation

Negative entropy gradient leads Rayleigh-Taylor instability
(Cold heavy matter is put over hot light matter)

Rayleigh-Taylor convection transfer energy outward.

Proto Neutron Star

Cooler than the initial state but $\nu$ heat is active

Hotter than the initial state
Shape of the explosion?

Many hot bubble is observed.

That is evidence of strong convection.
Explosive Nucleosynthesis

Finally Ni is produced behind the shock and that is the main fuel of supernovae optical light curve.

Heavy Nuclei

n,p

n,p

n,p

Heavy Nuclei

13
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  r-process nucleosynthesis?
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  r-process nucleosynthesis?
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- Summary
1D artificial Explosion

Heating rate is 5 times enhanced. \( E_{\text{exp}} = 0.8 \times 10^{51}\text{ergs} \)

Does r-process occur?
1D artificial Explosion

Does r-process occur? No. Only weak-r(LEEP)
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Rotation

Rotational energy(T)/gravitational energy(W) reach some criteria => Spiral mode arises

In the rigid ball: 14%

In SNe case: ~ 6% (Called low-T/W instability)
Rotation

Spiral wave transfer the energy to the outer region. Finally explosion is found!
Strong expansion is found at equatorial plane

(see also Nakamura+14 and Iwakami+14)
Convective Effects

Entropy $\sim T^3/\rho$

Heated by $\nu$ neutrino

Fe $\Rightarrow$ n, p cooled by photo-dissociation

Energy transport by thermal convection

Energy transport by Rotation and Magnetic field

Proto Neutron Star

$\sim 200$ km

$\sim 20$ km

$\sim 100$ km

$Y_e \sim 0.1$

$Y_e \sim 0.5$

$\Rightarrow$ Possible r-process site?
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Toward making convincing model

Multi-D model is very delicate that depends on input physics and methods strongly!

2D models for multiple progenitors
- Bruenn+12: all explode
- Mueller+13: almost all explode
- Dolence+14: not explode
- Nakamura+14: all explode
- Suwa +14: half of them explode
- Hanke in prep: almost all explode

3D models for multiple progenitors
- Hanke in prep: not explode (3model)
- Takiwaki in prep: half of them explode (failed in heavier progenitor)
Toward making convincing model

Difference of 5% in heating rate completely change the fate.

To make convincing model, the error should be < 5%.
Method of $\nu$ transport

For simple spherical computation, the result is rather consistent. But 10-20% of difference is observed.
Beta reaction in heavy nuclei can change the supernova physics dramatically! We have to update on this issue.

Updated version employs the reaction below.

\[
\nu_e + e^- \rightarrow \nu_e + e^- \quad \text{Mezzacappa & Bruenn 1993}
\]

\[
A + e^- \rightarrow A' + \nu_e \quad \text{Bruenn+ 1985 (We have to update to Langanke+ 2003)}
\]
Neutrino oscillation

Self interaction begin \(~500\text{km}\). Not affect to the shock revival.
Caveat: single angle approximation

(see also Dasgupta+2012)
General relativity

Susceptibility to the explosion

Full GR
Newtonian
Effective GR

GR > Newtonian > Eff-GR

Mueller et al. 2012
Summary

- 3D simulation is available.
  => a few successful models
  => r-process for smaller A
- Rotation and Magnetic field
  => possibly r-process site
- Help of nuclear and neutrino theory
  is surely important
  to make convincing model.
Does rotation affect the shock revival?

1D => no shock revival
s11.2 : No
N13   : Yes
s27    : Yes
How energetic is that?

Observe $0.1 - 0.4 \times 10^{51}$ erg! It’s close to $10^{51}$ erg!
Viscosity as the hidden parameter

1D
ATV

2D
HLL

3D
HLL

Shock radius [km]
Time after bounce [ms]
Comparison of the shock radius

Our simulation overestimates the shock radius compared to that of the new version (but new version may underestimate that?).