Systematic Studies of the Post-Shock-Revival Evolutions in Core Collapse Supernovae with Parametric Progenitor Models

Yu Yamamoto (Waseda Univ)
Collaborator: Shoichi Yamada (Waseda Univ)

01/09/2015 @ Numazu workshop
Systematic Studies of Explosion Energy and Nickel Mass in Core Collapse Supernovae with Parametric Progenitor Models

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Contents

• Introduction

• Method  1) Pre-supernova structure  
             2) Shock revival & Explosion

• Results  1) Explosion energy & Nickel mass  
              2) Explosion energy properties

• Summary

• Future works
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• Summary
  Nuclear energy release is important for explosion energy !!

• Future works
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Introduction : Explosion Energy problem

Thanks to computational development, CCSNe theorists are now able to perform

The first principle calculations
- Realistic EoS
- neutrino transport scheme
- multi-dimension hydrodynamic (2D & 3D!!)
- (GR treatment: more advanced)
Introduction: Explosion Energy problem

Thanks to computational development, CCSNe theorists are now able to perform

The first principle calculations
- Realistic EoS
- neutrino transport scheme
- multi-dimension hydrodynamic (2D & 3D!!)
- (GR treatment: more advanced)

in some cases

Several groups have succeed in reviving stalled shock. The challenge has been changed to reproduce “observations”. 
Introduction: Explosion Energy problem

One of the most important and well known observation

The first principle calculations
- Realistic EoS
- neutrino transport scheme
- multi-dimension
- (GR)

What is the result from the first principle calculations?
Introduction: Explosion Energy problem

Muller & Janka 2015

The first principle calculations
- Realistic EoS
- neutrino transport scheme
- multi-dimension
- (GR)

0.1 - $8 \times 10^{50}$ erg

Nakamura +14

large amount of binding energy

Bruenn +14

time evolution of $E_{\text{exp}}$
Introduction: Explosion Energy problem

Muller & Janka 2015

The first principle calculations

Canonical Explosions (Recent observation)

Pejcha & Prieto 2015

Nakamura +14

Bruenn +14

large amount of binding energy

time evolution of $E_{\text{exp}}$

$E_{\text{exp}} - M_{\text{Ni}}$

$M_{\text{Ni}}/M_\odot$

$log (M_{\text{Ni}}/M_\odot) = 1.49^{+0.27}_{-0.19} log (E_{\text{exp}}/10^{50} \text{ ergs}) - 2.90^{+0.20}_{-0.24}$

$\Sigma = 0.14^{+0.04}_{-0.03}$

5 SNII-P

13 SNII-P
Introduction: Explosion Energy problem

Muller & Janka 2015

The first principle calculations
- Realistic EoS
- neutrino transport scheme
- multi-dimension
- (GR)

failed

time evolution of $E_{\text{exp}}$

failed?

large amount of binding energy

not sufficient

partly success?

Bruenn +14
Introduction: Explosion Energy problem

So why this happen? What is the main reason of “weak” explosion when one conduct “realistic” computation?

Lack of calculation time.

Progenitor dependence (Initial value problem)

Our interest

- How the stellar structure influence $E_{\text{exp}}$?
Introduction: Explosion Energy problem

So why this happen? What is the main reason of “weak” explosion when one conduct “realistic” physics computation?

• How the stellar structure influence $E_{\text{exp}}$?
  -> What kind of structure prefers strong explosion?

Progenitor dependence (Initial value problem)

Lack of calculation time.

Our interest
Introduction: Explosion Energy problem

So why this happen? What is the main reason of “weak” explosion when one conduct “realistic” physics computation?

↓

Lack of calculation time.

Progenitor dependence (Initial value problem)

previous research
exploadability: compactness O’Connor & Ott 2011

How does this compactness affect $E_{\text{exp}}$?
Introduction: Realistic progenitor trends

Core and Si+S mass distribution as function of progenitor mass

Cartoon of stellar structure
Introduction: Realistic progenitor trends

Core and Si+S mass distribution as function of progenitor mass

It is apparent that
- non-monotonic
- large scatter appear especially in Si+S mass
Introduction: Realistic progenitor trends

Core and Si+S mass distribution as function of progenitor mass

Is there any much clearer trends in pre-supernova structure?

- large scatter appear especially in Si+S mass

H layer

Fe core

QSE

O

Si+S: $M_{SiS}$

Si+S+O

$M_{c}$

$M_{ZAMS}$ [M$_\odot$]

Woosley +02

$M_{c}$

$M_{SiS}$

$M_c [M_\odot]$
Introduction: Realistic progenitor trends investigating Woosley +02 models

ρ - S, Ye plane of Fe core for 30 progenitors (11-40 Msol)

upper: Entropy

lower: Ye

heavy

light
Introduction: Realistic progenitor trends investigating Woosley +02 models

ρ - S, Ye plane of Fe core for 30 progenitors (11-40 Msol)

Sorted by ① density jump  ② Maximum entropy value
Introduction: Realistic progenitor trends investigating Woosley +02 models

$\rho$ - S, Ye plane of Fe core for 30 progenitors (11-40 M$_{\odot}$)

Our discovery

*Fe core* structure may be classified in 3 categories.
Introduction: Realistic progenitor trends investigating Woosley +02 models

ρ - S, Ye plane of Fe core for 30 progenitors (11-40 Msol)

To perform systematic study, we first explore the core and Si+S mass dependence on $E_{exp}$ and Ni.

Our discovery

Fe core structure may be classified in 3 categories.
Our discovery

Fe core structure may be classified in 3 categories.

Introduction: Realistic progenitor trends investigating Woosley +02 models

$\rho - S$, Ye plane of Fe core for 30 progenitors (11-40 Msol)

Using “Medium (M)” structure for providing our toy models
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Method: 1) Constructing pre-supernova parameter set: \((M_c, M_{SiS})\)

\[
3 \times 2 = 6 \text{ models}
\]

We choose

\[
M_c = \begin{cases} 1.30 M_\odot, & 1.40 M_\odot, & 1.50 M_\odot \end{cases}
\]

\[
M_{SiS} = \begin{cases} 0.09 M_\odot, & 0.18 M_\odot \end{cases}
\]

consisted of 7 layers

<table>
<thead>
<tr>
<th>\text{core}</th>
<th>\text{QSE}</th>
<th>\text{Si+S+O}</th>
<th>\text{O+Mg+Si}</th>
<th>\text{O+Ne+Mg}</th>
<th>\text{C+O}</th>
<th>\text{C+O+He}</th>
<th>\text{He}</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{M [M}_\odot\text{]}</td>
<td>\text{M}_c</td>
<td>\text{M}_{SiS}</td>
<td>0.36-\text{M}_{SiS}</td>
<td>0.09</td>
<td>2.21-\text{M}_c</td>
<td>0.15</td>
<td>\gtrsim 0.10</td>
</tr>
<tr>
<td>\text{S [k}_B/\text{nuc]}</td>
<td>\text{eq.1}</td>
<td>3.3</td>
<td>4.0</td>
<td>5.0</td>
<td>5.9</td>
<td>6.5</td>
<td>7.6</td>
</tr>
<tr>
<td>\text{chemical abundance}</td>
<td>\text{NSE}</td>
<td>\text{QSE}</td>
<td>X_{Si} = 0.45, &amp; X_O = 0.80, &amp; X_O = 0.70, &amp; X_C = 0.20, &amp; X_C = 0.30, &amp; X_{He} = 1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>X_S = 0.35, &amp; X_{Mg} = 0.15, &amp; X_{Ne} = 0.25, &amp; X_O = 0.80 &amp; X_O = 0.60, &amp; X_{He} = 0.10</td>
<td></td>
<td></td>
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Note: In this paper we pay attention mainly to the core mass, \(M_c = 1.3, 1.4, 1.5 M_\odot\) and Si+S layer mass, \(M_{SiS} = 0.09, 0.18 M_\odot\).
Method: 1) Constructing pre-supernova

Parameter set: \( (M_c, M_{SiS}) \)

3 \times 2 = 6 models

We choose

<table>
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<th>(M_c)</th>
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<tr>
<td>1.30 (M_\odot)</td>
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<tr>
<td>1.40 (M_\odot)</td>
<td></td>
</tr>
<tr>
<td>1.50 (M_\odot)</td>
<td>0.18 (M_\odot)</td>
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297 nuclei

Consisted of 7 layers

<table>
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<tr>
<th>M ([M_\odot])</th>
<th>(M_c)</th>
<th>(M_{SiS})</th>
<th>Si+S+O</th>
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<th>O+Ne+Mg</th>
<th>C+O</th>
<th>C+O+He</th>
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<td>6.5</td>
<td>7.6</td>
<td>12.0</td>
</tr>
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<td>Chemical abundance</td>
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<td>X_{Si} = 0.35, (X_{Mg} = 0.15, X_{Ne} = 0.25, X_O = 0.80)</td>
<td></td>
<td>(X_O = 0.60, X_{Mg} = 0.05)</td>
<td>(X_{He} = 0.10)</td>
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Note: In this paper we pay attention mainly to the core mass, \(M_c = 1.3, 1.4, 1.5M_\odot\) and Si+S layer mass, \(M_{SiS} = 0.09, 0.18M_\odot\).

1) \(S(\rho)\)

2) \(S : \text{constant for each layers}\)

\(Y_e(\rho)\)

\(Y_e\)
Method: 1) Constructing pre-supernova

Parameter set: \((M_c, M_{SiS})\)

- \(3 \times 2 = 6\) models
- Consisted of 7 layers

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<td>1.10</td>
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\(X_S = 0.45, X_O = 0.80, X_O = 0.70, X_C = 0.20, X_C = 0.30, X_{He} = 1.00\)

\(X_S = 0.35, X_{Mg} = 0.15, X_{Ne} = 0.25, X_O = 0.80, X_O = 0.60, X_{He} = 0.10\)

Note: In this paper we pay attention mainly to the core mass, \(M_c = 1.3, 1.4, 1.5 M_\odot\), and Si+S layer mass, \(M_{SiS} = 0.09, 0.18 M_\odot\).

Ex) Density and entropy profiles for toy models
Method: 1) Constructing pre-supernova parameter set: \( (M_c, M_{SiS}) \)

3 \( \times \) 2 = 6 models consisted of 7 layers

<table>
<thead>
<tr>
<th>( M_c ) [( M_\odot )]</th>
<th>( M_{SiS} )</th>
<th>( X_{Si} )</th>
<th>( X_O )</th>
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Ex) Density and entropy profiles for toy models

\( S_{env} \): step function suited for systematic study

Note: In this paper we pay attention mainly to the core mass, \( M_c = 1.3, 1.4, 1.5M_\odot \) and Si+S layer mass, \( M_{SiS} = 0.09, 0.18M_\odot \).
Method: 1) Constructing pre-supernova

parameter set: \((M_c, M_{SiS})\)

- \(3 \times 2 = 6\) models
- total 7 layers

The structures are sensitive to slight mass differences (\(\sim 0.1\,\text{Msun}\)), particularly after O layer.

ex) Density profiles for toy models

![Density profiles](image)
Progenitor dependence on stalled shock phase

balance between

1) mass accretion $\dot{M}$  \quad \longleftrightarrow \quad 2) neutrino luminosity $L_\nu$
Progenitor dependence on stalled shock phase

balance between

1) mass accretion $\dot{M}$

2) neutrino luminosity $L_\nu$

ram pressure

shock front

$R_{sh} \sim 10^7 \text{cm}$

schematic picture of neutrino heating

$R_{sh} \sim 10^{6-7} \text{cm}$

gain radius

$L_\nu$

$R_g$

$T_\nu$
Progenitor dependence on stalled shock phase

balance between

1) mass accretion $\dot{M}$ \quad \quad \quad 2) neutrino luminosity $L_\nu$

- density profile
(passage of layers; Fe $\rightarrow$ Si $\rightarrow$ O layer)

ram pressure

shock front

$R_{sh} \sim 10^7 \text{ cm}$

$R_{sh} \sim 10^6 - 7\text{ cm}$

gain radius

PNS

- core mass (gravitational source)

$\frac{L_\nu}{R_g T_\nu}$
Progenitor dependence on stalled shock phase

balance between

1) mass accretion $\dot{M}$

2) neutrino luminosity $L_\nu$

- density profile
  (passage of layers; Fe $\rightarrow$ Si $\rightarrow$ O layer)

- core mass (gravitational source)

Both $\dot{M}$, $L_\nu$ rely on progenitor structure
Idea of shock formation and revival calculation

1) mass accretion $\dot{M}$ \hspace{1cm} 2) neutrino luminosity $L_v$

balance between

- ram pressure
- $\dot{M}$ - density profile

Our aim: Experimental study using parametric pre-supernova stages

- $R_{sh} \sim 10^7$ cm
- controlling shock revival time (early or late)
- core mass (gravitational source)
- nuclear density EoS
- 

parameter

$\frac{L_v}{R_g T_v}$
Idea of shock formation and revival calculation

balance between

1) mass accretion $\dot{M}$  
2) neutrino luminosity $L_\nu$

ram pressure

$\dot{M}$ - density profile

(passage of layers: Fe $\rightarrow$ Si $\rightarrow$ O layer)

Our aim: **Experimental study using parametric pre-supernova stages**

- i) controlling shock revival time (early or late)
- ii) conduct long time simulation
- remove PNS
- core mass (gravitational source)
- nuclear density EoS

ignore
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Method: 2) Shock formation and evolution

Propose: Calculate $E_{\text{Exp}}$ and $M_{\text{ni}}$ for 6 toy models with controlling explosions

employing 3 stages for conducting experimental study

I) Collapse,  II) Stalled Shock,  III) Shock revival & evolution
Method: 2) Shock formation and evolution

Propose: Calculate $E_{\text{exp}}$ and $M_{\text{ni}}$ for 6 toy models with controlling explosions

employing 3 stages for conducting experimental study

I) Collapse,  II) Stalled Shock,  III) Shock revival & evolution

Hydro

-Using ZEUS code for simulating hydrodynamics

1D: ODE (Ordinary Differential Equation)
Method: 2) Shock formation and evolution

Propose: Calculate $E_{exp}$ and $M_{ni}$ for 6 toy models with controlling explosions

employing 3 stages for conducting experimental study

I) Collapse, II) Stalled Shock, III) Shock revival & evolution

- Light bulb approximation instead of neutrino transport solver

\[

v_e + n \leftrightarrow e^- + p \\
\bar{v}_e + p \leftrightarrow e^+ + n

\]
Method: 2) Shock formation and evolution

Propose: Calculate $E_{\text{exp}}$ and $M_{\text{ni}}$ for 6 toy models with controlling explosions

employing 3 steps for conducting experimental study

I) Collapse, II) Stalled Shock, III) Shock revival & evolution

ZEUS2D
- No neutrino

ODE
- Light bulb

ZEUS2D
- Light bulb

Nuclear

-Take into proper account nuclear abundance evolution

$$\text{NSE} \left( T_9 \geq 7.0 \right): \text{297 nuclei}$$
$$\text{nuclear network} \left( T_9 < 7.0 \right): \text{28 nuclei + single averaged nucleus}$$
Method: 2) Shock formation and evolution

Propose: Calculate Eexp and Mni for 6 toy models

employing 3 steps for conducting experimental study

I) Collapse, II) Steady Shock, III) Shock revival & evolution

Starting from 6 toy models:
- Run 1D hydrodynamic calculation for collapse in order to obtain $M$ histories.
Method: 2) Shock formation and evolution

Propose: Calculate $E_{\text{exp}}$ and $M_{\text{ni}}$ for 6 toy models

employing 3 steps for conducting experimental study

I) Collapse, II) Steady Shock, III) Shock revival & evolution

Starting from 6 toy models:
- Run 1D hydrodynamic calculation for collapse in order to obtain $M$ histories.

Density Evolution

Mass Accretion History
Method: 2) Shock formation and evolution

Propose: Calculate $E_{\text{exp}}$ and $M_{\text{ni}}$ for 6 toy models

employing 3 steps for conducting experimental study

I) Collapse,  II) Steady Shock,  III) Shock revival & evolution

Starting from 6 toy models
: Run 1D hydrodynamic calculation for collapse in order to obtain $M$ histories.

matters are sinking into “hole”:  1) $t \lesssim 200\text{ms}$ : mass accretion

2) $t \gtrsim 200\text{ms}$ : mass accretion

Density Evolution

Mass Accretion History
Method: 2) Shock formation and evolution

Propose: Calculate $E_{\text{exp}}$ and $M_{\text{ni}}$ for 6 toy models

employing 3 steps for conducting experimental study

I) Collapse, II) Steady Shock, III) Shock revival & evolution

Starting from 6 toy models:
- Run 1D hydrodynamic calculation for collapse in order to obtain $M$ histories.

No core bounce
No shock formation

matters are sinking into “hole”:
- $t \lesssim 200\,\text{ms}$: mass accretion
- $t \gtrsim 200\,\text{ms}$: mass accretion

Density Evolution

Mass Accretion History
Method: 2) Shock formation and evolution

Propose: Calculate Eexp and Mni for 6 toy models

employing 3 steps for conducting experimental study

1) Collapse, 2) Steady Shock, 3) Shock revival & evolution

Starting from 6 toy models
: Run 1D hydrodynamic calculation for collapse
in order to obtain \( M \) histories.

No core bounce
No shock formation

steady shock solution

matters are sinking into “hole”:
1) \( t \lesssim 200 \text{ms} \) : mass accretion
2) \( t \gtrsim 200 \text{ms} \) : mass accretion

steady

decrease
Method: 2) Shock formation and evolution
Propose: Calculate Eexp and Mni for 6 toy models employing 3 steps for conducting experimental study

I) Collapse,  II) Stalled Shock,  III) Shock revival & evolution

Steady shock solution (ODE)

: Taking 3 different $L_\nu$ with 6 $\dot{M}$ histories to produce total 18 stalled 1D shock solutions.

\[ L_\nu = 2.0, \ 2.3, \ 2.5 \times 10^{52} \text{ erg / s} \]

\[ \left( L_\nu, \dot{M} \right) : \text{parameter} \]

\[ \rho T v_r \frac{dS}{dr} = Q_E \]

\[ \rho N_A v_r \frac{dY_e}{dr} = Q_N \]

\[ v_r \frac{dY_j}{dr} = f_j (\rho, S, \{Y_k\}) \]

nucler reaction rates

\[ 4\pi r^2 \rho v_r = -\dot{M} \]

\[ \rho v_r \frac{dv_r}{dr} = -\frac{dP}{dr} - \rho \frac{GM_r}{r^2} \]
Method: 2) Shock formation and evolution
Propose: Calculate $E_{\text{exp}}$ and $M_{\text{ni}}$ for 6 toy models

employing 3 steps for conducting experimental study

I) Collapse, II) Stalled Shock, III) Shock revival & evolution

Steady shock solution (ODE)
: Taking 3 different $L_\nu$ with 6 $\dot{M}$ histories to produce total 18 stalled 1D shock solutions.

$$L_\nu = 2.0, \ 2.3, \ 2.5 \times 10^{52} \ erg / s$$

shock front $\left( L_\nu, \dot{M} \right)$ : parameter

ex) Entropy profiles
**Method: 2) Shock formation and evolution**

**Propose:** Calculate $E_{\text{exp}}$ and $M_{\text{ni}}$ for 6 toy models

employing 3 steps for conducting experimental study

1. **Collapse**
2. **Steady Shock**
3. **Shock revival & evolution**

**Steady shock**
- Initial condition

**Density evolution**
- Starting from steady shock solution.

Neutrino heating and shock revival
- For shock revival and explosion phase, we run 1D and 2D hydrodynamic calculation assuming light bulb approximation.
Method: 2) Shock formation and evolution

Propose: Calculate $E_{\text{exp}}$ and $M_{\text{ni}}$ for 6 toy models

Employing 3 steps for conducting experimental study:

Steady shock:
- Initial condition

Density evolution
- After several back and force motion
- Shock propagate outward

Neutrino heating and shock revival:
- For shock revival and explosion phase, we run 1D and 2D hydrodynamic calculation assuming light bulb approximation.
Method: 2) Shock formation and evolution

Propose: Calculate $E_{\text{exp}}$ and $M_{\text{ni}}$ for 6 toy models

employing 3 steps for conducting experimental study

1) Collapse,  II) Steady Shock,  III) Shock revival & evolution

Neutrino heating and shock revival
: For shock revival and explosion phase, we run 1D and 2D hydrodynamic calculation assuming light bulb approximation.

1D: 18 models, 2D: 8 models

$$L_{\nu,52} = 2.0, 2.3, 2.5 \times$$

$$M_c = 1.30, 1.40, 1.50 \times$$

$$M_{SiS} = 0.09, 0.18$$

Steady shock: Initial condition

$\rho$ [g/cm$^3$] vs $R$ [cm]
Method: 2) Shock formation and evolution
Propose: Calculate \( E_{\text{exp}} \) and \( M_{\text{Ni}} \) for 6 toy models employing 3 steps for conducting experimental study

- \( t_{\text{pb}} = 0.03 \) sec
- \( M \): evolve
- \( L_{\nu} \): fixed
- \( M \): evolve
- \( L_{\nu} \): decay
- \( M \): evolve
- Explosion energy
- Nickel mass \( \sim < 2 \) sec

Neutrino heating and shock revival:
For shock revival and explosion phase, we run 1D and 2D hydrodynamic calculation assuming light bulb approximation.

1D: 18 models, 2D: 8 models

Steady shock:
Initial condition
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Result 1: Explosion Energy vs Nickel mass

Total: 26 models, 1D: 18 models, 2D: 8 models

\[ E_{\text{exp}} = \sum_{v_r>0, e_{\text{tot}}>0} e_{\text{tot}} \Delta V, \]

\[ e_{\text{tot}} = e_{\text{kin}} + e_{\text{int}} + e_{\text{grav}}. \]
Result 1: Explosion Energy vs Nickel mass

Total: 26 models, 1D: 18 models, 2D: 8 models

Observation data

\[ E_{\text{exp}} = \sum_{v_r > 0, e_{\text{tot}} > 0} e_{\text{tot}} \Delta V, \]

\[ e_{\text{tot}} = e_{\text{kin}} + e_{\text{int}} + e_{\text{grav}}; \]
Result 1: Explosion Energy vs Nickel mass

Total: 26 models, 1D: 18 models, 2D: 8 models

1D shows strong correlation (black solid line)

Small core (red+green)

Strong explosion

Pejcha+15
Result 1: Explosion Energy vs Nickel mass

Total: 26 models, 1D: 18 models, 2D: 8 models

- 1D shows strong correlation (black solid line)

$$M_{NI} \propto E_{exp}^{0.70}$$

$$E_{exp} = \sum_{v_r>0, e_{tot}>0} e_{tot} \Delta V,$$

$$e_{tot} = e_{kin} + e_{int} + e_{grav};$$

Pejcha+15
Result 1: Explosion Energy vs Nickel mass

Total: 26 models, 1D: 18 models, 2D: 8 models

- 1D shows strong correlation (black solid line)
- Only pink area, however, can be explained

\[ M_{Ni} \propto E_{exp}^{0.70} \]

\[ E_{exp} = \sum_{v_r>0, e_{tot}>0} e_{tot} \Delta V, \]

\[ e_{tot} = e_{kin} + e_{int} + e_{grav}. \]

Pejcha+15
Result 1: Explosion Energy vs Nickel mass

Total: 26 models, 1D: 18 models, 2D: 8 models

Explaining obs better!!

2D shows different correlation (red solid line)
Result 1: Explosion Energy vs Nickel mass

Total: 26 models, 1D: 18 models, 2D: 8 models

Explaining obs better !!

2D shows different correlation (red solid line)

small core

strong explosion
Result 1: Explosion Energy vs Nickel mass

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Explaining obs better!!

Fall back to PNS
Result 1: Explosion Energy vs Nickel mass

Total: 26 models, 1D: 18 models, 2D: 8 models

2D shows different correlation (red solid line)

Explaining obs better!!

Fall back to PNS

larger Si+S mass (filled) leads to smaller $M_{Ni}$
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Result 2: Explosion energy properties

\[ \dot{M}_{\text{rev}} = E_{\text{exp}} \]

plane

1D : 18 models

\[ L_v, 52 = 2.5, 2.3, 2.0 \]

mass accretion rate at shock revival:

\[ \dot{M}_{\text{rev}} \quad \left[ \dot{M}_\odot \, \text{s}^{-1} \right] \]
Result 2: Explosion energy properties

\[
\dot{M}_{\text{rev}} - E_{\text{exp}} \quad \text{plane}
\]

As well as
\[M_{Ni} - E_{\text{exp}}\]

strong correlation

mass accretion rate at shock revival:
\[\dot{M}_{\text{rev}} \quad [M_\odot \text{s}^{-1}]\]

1D : 18 models
Result 2: Explosion energy properties

\[ \dot{M}_{\text{rev}} - E_{\text{exp}} \]

plane

1D: 18 models, 2D: 8 models

strong correlation

2D also obey 1D correlation line

\[ M_c = 1.30M, 1.40M, 1.50M \]

\[ M_{\text{SiS}} = 0.09M, 0.18M \]

\[ L_v, 52 = 2.5, 2.3, 2.0 \]
Result 2: Explosion energy properties

- 1D: 18 models, 2D: 8 models
- 2D also obey 1D correlation line
- Dimensionless strong correlation

\[ E_{\text{exp}} \propto \dot{M}_{\text{rev}}^{1.61} \]
Result 2: Explosion energy properties

\[
\dot{M}_{\text{rev}} \sim E_{\text{exp}}
\]

plane

1D: 18 models, 2D: 8 models

Dimensionless

\[E_{\text{exp}} \propto \dot{M}_{\text{rev}}^{1.61}\]

strong correlation

\[\dot{M}_{\text{rev}} \gtrsim 0.35 M_\odot \text{s}^{-1}\]

strong explosion
Result 3: Explosion energy properties 

Why \( \dot{M}_{\text{rev}} - E_{\text{exp}} \) relation appear?

Introducing eject mass: \( - M_{T_p} \)

\[
M_{T_p} = \sum \Delta m^{(n)}
\]

\( T_{P,9}^{(n)} > 5.0, v_r^{(n)} > 0 \)

Schematic picture of ejecta

engine of eject mass \([\text{Msol}]\)
Result 3: Explosion energy properties

Why $\dot{M}_{\text{rev}} - E_{\text{exp}}$ relation?

Introducing ejecta mass: $M_{Tp}$

$M_{Tp} = \sum \Delta m^{(n)}$

$T_{P,9}^{(n)} > 5.0, v_r^{(n)} > 0$

engine of eject mass

peak temperature

ejecta

engine

shock expansion
Result 3: Explosion energy properties

Why \( \dot{M}_{\text{rev}} \sim E_{\text{exp}} \) relation?

Introducing ejecta mass: \( M_{Tp} \)

\[
M_{Tp} = \sum_{T_{P,9}^{(n)}>5.0, \nu_{r}^{(n)}>0} \Delta m^{(n)}
\]

- 1. neutrino heating
- 2. nuclear recombination: 
  \[ p, n \rightarrow \alpha \]
  \[ \alpha \rightarrow \text{iron group} \]
Result 3: Explosion energy properties

Why \( \dot{M}_{\text{rev}} - E_{\text{exp}} \) relation?

Introducing ejecta mass: \( M_{Tp} \)

\[
M_{Tp} = \sum \Delta m^{(n)} \\
\text{subject to } T_{p,9}^{(n)}>5.0, \nu_{r}^{(n)}>0
\]

Engine of eject mass

- 1. Neutrino heating
- 2. Nuclear recombination
  - \( p, n \rightarrow \alpha \)
  - \( \alpha \rightarrow \text{iron group} \)

Peak temperature

Ejecta

Engine

Shock expansion

Responsible for heating source
Result 3: Explosion energy properties

\[ \dot{M}_{\text{rev}} - M_{TP} \]

\[ M_{TP} - E_{\text{exp}} \]

1D : 18 models, 2D : 8 models

engine of eject mass

\[ M_{TP} = \sum \Delta m^{(n)} \]

\[ T_{P,9}^{(n)} > 5.0, \nu_{r}^{(n)} > 0 \]
Result 3: Explosion energy properties

\[ \dot{M}_{\text{rev}} \sim M_{TP} \]

\[ M_{TP} \sim E_{\text{exp}} \]

1D: 18 models, 2D: 8 models

Strong correlation

Dimension less (?)
Result 3: Explosion energy properties

\[ \dot{M}_\text{rev} - M_{Tp} \]

\[ M_{Tp} \propto \dot{M}_\text{rev}^{1.47} \]

\[ M_{Tp} - E_{exp} \]

\[ E_{exp} \propto M_{Tp}^{1.07} \]

1D : 18 models, 2D : 8 models

Strong correlation

Dimension less (?)
Result 4: Explosion energy properties

Averaged energy sources

1D: 18 models, 2D: 8 models

\[ \varepsilon_{nuc} = \frac{E_{nuc}}{M_{TP}/m_b} \]

\[ \varepsilon_{\nu} = \frac{E_{\nu}}{M_{TP}/m_b} \]

\[ E_i = \sum Q_i^{(n)} \Delta V \Delta t^{(n)} \]

\( i = \text{nuc, } \nu \)

\( v_r > 0, \varepsilon_{f\nu} > 0 \)

Unit: [MeV/cc/sec]
Result 4: Explosion energy properties

1D : 18 models, 2D : 8 models

Averaged energy sources

\[ \varepsilon_{\text{nuc}} = \frac{E_{\text{nuc}}}{M_{TP}/m_b} \quad \varepsilon_{\nu} = \frac{E_{\nu}}{M_{TP}/m_b} \]

\[ E_i = \sum_{v_r>0, \epsilon_{\text{lar}}>0} Q_i^{(n)} \Delta V \Delta t^{(n)} \]

5 - 6MeV/nuc \quad 1 - 2MeV/nuc

\[ \varepsilon_{\text{nuc}} > \varepsilon_{\nu} \]

nuclear energy release contribute more than neutrino heating
Result 4: Explosion energy properties

Averaged energy sources

\[ \varepsilon_{\text{nuc}} = \frac{E_{\text{nuc}}}{M_{TP}/m_b} \quad \varepsilon_{\nu} = \frac{E_{\nu}}{M_{TP}/m_b} \]

\[ E_i = \sum_{\nu_r>0, \epsilon_{\text{for}}>0} Q_i^{(n)} \Delta V \Delta t^{(n)} \]

1D: 18 models, 2D: 8 models

- 5 - 6 MeV/nuc
- 1 - 2 MeV/nuc

\[ \varepsilon_{\text{nuc}} > \varepsilon_{\nu} \]

Neutrino heating is still important for liberating matter from binding, hence shock revival mechanism!!
Result 4: Explosion energy properties

\[ \varepsilon_{nuc} = \frac{E_{nuc}}{M_{TP}/m_b} \]
\[ \varepsilon_{\nu} = \frac{E_{\nu}}{M_{TP}/m_b} \]

\[ E_i = \sum_{v_r>0, \epsilon_{for}>0} Q_i^{(n)} \Delta V \Delta t^{(n)} \]

1D : 18 models, 2D : 8 models

Averaged energy sources

\[ \varepsilon_{nuc}, \varepsilon_{\nu} \]

1D > 2D: artificial underestimation
Result 4: Explosion energy properties

Averaged energy sources

\[ \varepsilon_{\text{nuc}} = \frac{E_{\text{nuc}}}{M_{T_P}/m_b} \quad \varepsilon_{\nu} = \frac{E_{\nu}}{M_{T_P}/m_b} \]

1D : 18 models, 2D : 8 models

\[ E_i = \sum_{r>0, \epsilon_r>0} Q^{(n)} \Delta V \Delta t^{(n)} \]

\[ \varepsilon_{\text{nuc}}, \varepsilon_{\nu} \]

1D > 2D: artificial underestimation

wind component already recombined to \( \alpha \)
ejecta
Result 4: Explosion energy properties

\[ \varepsilon_{exp} - M_{TP} \] relation

1D: 18 models, 2D: 8 models

\[ \varepsilon_{exp} = \frac{E_{exp}}{M_{TP}/m_b} \text{ [MeV/nuc]} \]
**Result 4: Explosion energy properties**

\[ \varepsilon_{exp} - M_{TP} \] relation  

1D : 18 models, 2D : 8 models

\[ \varepsilon_{exp} = \frac{E_{exp}}{M_{TP}/m_b} \]  

[MeV/nuc]

\[ \varepsilon_{exp} \text{ slightly increase as } M_{TP} \]

\[ 4 - 6 \text{ MeV/nuc} \]
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Summary

• We produce toy pre-supernova models to explore the hidden relation between inner stellar structure and explosion properties.

• Constructing the toy models by controlling Fe core and Si+S mass, we run 1D and 2D dynamical calculations to obtain the explosion energy and nickel mass.

• We found that early explosion is mandatory to produce the canonical explosion energy.

• The lighter Fe core mass is favorable for enhancing the explosion energy whereas the heavier Si+S mass show smaller Ni mass ejection in 2D.
Summary

• We also find the explosion energy strongly relies on mass accretion rate at shock revival time.

• Hot engine eject mass ($T_9 > 5.0$) show interesting correlation with both $\dot{M}_{rev}$ and $E_{exp}$.

• Nuclear energy release is essentially for explosion energy.
Underlying questions?

• Is the stellar properties we applied also seen in other stellar evolution groups?

• What determines the power law indexes we’ve seen in the explosion energy discussion? Do they change if we choose different $S$, $Ye$ function?

• Is it possible to provide light core with large entropy in “realistic” stellar evolution calculation?
Light core outcomes: Realistic vs. Toy model

Usually give “weak” explosion

ex) s11.2: \[ \sim 1 \times 10^{50} \text{ erg} \]
Light core outcomes: Realistic vs. Toy model

Usually give “weak” explosion
ex) s11.2: $\sim 1 \times 10^{50} \text{ erg}$

$\rho$ - $S$, $Y_e$ plane of Fe core

2/30 (majority) 20/30 8/30
Light core outcomes: Realistic vs. Toy model

Usually give “weak” explosion
ex) s11.2: $\sim 1 \times 10^{50}\ erg$

2/30 (majority) 20/30 8/30
Light core outcomes: Realistic vs. Toy model

Comparing density profiles

red: realistic, green: our model

\[ M_r - \rho, S \quad R - \rho, S \]

\[ M_c = 1.30 \]

similar density profile inside the core
Light core outcomes: Realistic vs. Toy model

Comparing density profiles

red: realistic, green: our model

\[ M_r - \rho, S \quad \text{and} \quad R - \rho, S \]

Large deviation appears from O layer

\[ M_c = 1.30 \]
Future work

Underlying questions?

• Is the stellar properties we applied also seen in other stellar evolution groups?
• What determines the exponent values we’ve seen in explosion energy discussion? Do they change if we choose different S, Ye function?

• Is it possible to provide light core with large entropy in “realistic” stellar evolution calculation?

rapid evolution:
mass transfer? rapid nuclear or weak interaction reactions? convective/turbulent motion?
Thank you for your attention