Nucleosynthetic signatures in magneto-rotational driven core-collapse supernovae

Nobuya Nishimura
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  - origin of heavy elements
  - energetic supernovae, GRBs, and nucleosynthesis
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based on
N. Nishimura, T. Takiwaki, and F.-K. Thieleman
(2013 in prep.)
$r$-process: "cosmic alchemy"

- origin of heavy elements (with s-process)
  - e.g., gold, actinide

- nuclear physics
  - rapid-neutron captures (related to unstable isotopes)

- Astronomical sites (?)
  - non-standard Supernova (SN)
  - neutron star mergers

Solar system abundance
Anders & Grevesse (1989)
r-process: physics & astronomical sites

- **high neutron density**
  - neutron rich matter from NS?
  - explosive events
    (<< 1 min, neutron’s half life)
  - separated from the s-process

-Astronomical sites
  - core-collapse supernova (formation of NS)
  - merger of NS-NS / BH-NS binary
    → short GRB? (*talk by Wanajo*)
  - “collapsar” jet or disk
    → long GRB? (*talk by Surman*)
Core-Collapse Supernovae: > 10 $M_{\odot}$

the end of the evolution

the core collapses

a proto-neutron star is formed

\[ p + e^- \rightarrow n + \nu_e \]

electron-capture neutronization

\[ n + \nu_e \rightarrow p + e^- \]

protoneutron star

neutrino ($\nu_e$)-burst

figure: wikipedia
core-collapse supernovae

- supernova ejecta → iron group elements including $^{56}$Ni
- neutrino-driven proto-neutron star wind

Wanajo 2013

- difficult to have suitable condition for the r-process
- not very neutron-rich ($>0.4$)
- not high entropy ($<200$)
- supported by several studies Fischer et al. 2010, Hüdepohl et al. 2010 etc.

→ alternative energetic supernova scenario?
Magnetohydrodynamic (MHD) SNe and magnetars

\( r \)-process studies

- 2D MHD-SNe
  - Nishimura et al. 2006
  - Fujimoto, Nishimura, and Hashimoto 2008 (central Black-Hole and disk)
- 3D MHD-SNe with neutrino
  - Winteler et al. 2012

hypernova/jet-like SN

- Magnetar
  - strong magnetic field
  \(~10^{15}\) G
  \((\sim 1\%\) of all neutron stars)
- Magneto-driven Supernovae?
  - GRB central engine
  - Hypernovae

3D MHD simulation
Winteler et al. (2012)
3D-MHD model with leakage scheme


MHD code :
FISH ( Käppeli et al. 2011 )
progenitor :
15Msun (Heger&Woosely 2002)
magnetic fields :
poloidal $5 \times 10^{12}$ [G] ( initial )

red: neutrino absorption
(green: no neutrino)

$M_{ej} = 0.672 \ 10^{-2}$ Msun

Ejected Mass [10^{-5} M_\odot]

Ejected Mass [M_\odot]

Mass Number
r-process in MHD-SNe: “prompt” vs “delayed”

- more long-term simulation model
- robustness of resulting r-process
- dependency on the explosion mechanism

- axisymmetric
- special relativistic MHD
- leakage scheme for neutrino cooling
- $25M_{\odot}$ WR star (Heger & Woosley)

**Time duration of explosion**

| $B_0$ (Gauss) | $T/|W|$ (ms) | 0.25%  | 1.0%  | 4.0%  |
|---------------|--------------|--------|--------|--------|
| $10^{10}$     | 122 ms       | 96 ms  | 104 ms |
| $10^{11}$     | 72 ms        | 27 ms  | 32 ms  |
| $10^{12}$     | 32 ms        | 20 ms  | 25 ms  |

Takiwaki et al. 2009
Amplification of magnetic fields via field wrapping

differential rotation
magnetic field line

top view
magnetic field lines

side view

Takiwaki 2009
Ejected matter: ejection motion and $Y_e$

path of ejected tracer particles (post-process)
$Y_e$ evolution for different ejecta

![Graph showing $Y_e$ evolution for different ejecta with annotations indicating ignored $\nu_e$-capture and r-process flow.](Image)
r-process in MHD-SNe: “prompt” vs “delayed”

successful r-process (prompt)
r-process is suppressed up to second peak (delayed)
r-process result (2/3): “weak” r-elements

“weak” r-process pattern (HD122563; Honda 2006)
### Nucleosynthesis Result: Key Amounts

<table>
<thead>
<tr>
<th>Type</th>
<th>B11TW0.25</th>
<th>B11TW1.00</th>
<th>B12TW0.25</th>
<th>B12TW1.00</th>
<th>B12TW4.00</th>
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<tbody>
<tr>
<td>Ejected Mass</td>
<td>delayed</td>
<td>prompt</td>
<td>prompt</td>
<td>prompt</td>
<td>prompt</td>
</tr>
<tr>
<td>( 10^{-2} M_{\odot} )</td>
<td>1.27</td>
<td>6.88</td>
<td>3.42</td>
<td>9.48</td>
<td>9.38</td>
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<tr>
<td>R-Proc. Mass</td>
<td>0.963</td>
<td>1.54</td>
<td>1.15</td>
<td>2.05</td>
<td>2.67</td>
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<tr>
<td>( 10^{-3} M_{\odot} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{56}\text{Ni} )</td>
<td>1.07*</td>
<td>-</td>
<td>0.63*</td>
<td>1.19*</td>
<td>1.21*</td>
</tr>
<tr>
<td>( 10^{-2} M_{\odot} )</td>
<td></td>
<td></td>
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</tbody>
</table>

* Minimum values (component in the first shock wave)

- Significant amount of r-process matter compared with normal supernova \( 10^{-5} M_{\odot} \) from PNS wind
- Low event rate ( \( \sim 0.1 - 1 \% \) of all supernova)

Have impact on chemical evolution/observation
optical observation:

smaller amount of $^{56}\text{Ni}$

faint SN?

our results

$^{56}\text{Ni}$ with magnetar formation

Maeda et al. 2007

SN2005bf (type Ib with double peak)

- $^{56}\text{Ni} \sim 0.02 - 0.06 \text{ M}_{\odot}$
- strong magnetic field $\sim 10^{15} \text{ G}$

XRF060218 (SN2006aj)

Mazzali et al. 2006, Maeda et al. 2007
Summary

• MHD-SNe are still possible candidate for r-process
  • prompt-magnetic-jets: "main" r-process
  • delayed-magnetic-jets: "weak" r-process?
• Large amount of r-process elements ($\sim 10^{-3} M_{\text{sun}}$)
• MHD-SNe are faint? and have relation to peculiar SN/XRF.

remaining problem

- Long-term simulations
- dependence of initial rotations and magnetic fields
- MHD-SN always produce "solar" r-process pattern?
- uncertainties of micro physics (neutrino, ...)
- cases of large off-axisymmetry
- physics of MHD amplification process (MRI, reconection ..)
  ...