MHD-SNe as an alternative r-process site:
A new mechanism ejects neutron-rich matter
induced by magneto-rotational instability

N. Nishimura
Keele U, UK

Collaborators
• T. Takiwaki (RIKEN), F.-K. Thielemann (Basel)
• H. Sawai (RIST/Waseda), S. Yamada (Waseda)
Contents of the talk

- Introduction: origin of r-process elements
- MHD-SNe as alternative source?
- Effects of MRI to ejecta
The “similarity” of r-process in observation

- many r-rich Galactic halo stars show agreement with solar pattern
- r-process has happened from the early Galaxy
- astrophysical models reproduce this common pattern (Z>40; A>90)

→ suggests existence of “main” r-process sites produces between 2nd and 3rd peak
Possible Astronomical site/scenario

r-process needs (e.g. Hoffman+ 1992)

- neutron rich ($Y_e < 0.5$)
- fast expansion (explosions)
- high entropy (if $Y_e > 0.2$)
  → explosive events,
  in which NS or BH involve

massive stars → SN → PNS → NS-NS/BH-NS merger → r-process?

neutrino-driven wind
Difficulty of Core-collapse Supernovae
(one main issue of the workshop?)

- Supernova explosion
  - mainly produces iron group
    (talks by Kotake, Sumiyoshi, Takiwaki)
  - not neutron-rich
    - external: EC-SNe (∼8 \(M_{\odot}\) stars)
- Proto-NS wind
  - not high entropy
  - \(Y_e\) is not low enough
  - external \(\nu\) p-process (\(A < 100\))

Wanajo 2013
Difficulty of NS-NS mergers (However ...)

Goriely+ 2011 (e.g., Korobkin+ 2011, Rosswog+ 2013)

dynamical ejecta
too neutron-rich
to produces solar pattern

But, new NS-NS simulations can solve this problem? (Wanajo+ 2014)
see, Wanajo’s Talk!

dynamical ejecta
with neutrino-driven ejecta in later phase
We need a new paradigm?

- Core-collapse supernovae
  - ejecta is not neutron-rich enough
  - minor contribution to r-process observations?

- NS-NS mergers
  - ejecta is too neutron-rich
  - sophisticated treatment of neutrino, EOS can solve the problem
  - most likely (at least heavier than 2nd peak)

→ Alternative explosion scenario of CC-SNe
  - driven by rotation and magnetic fields
  - different nucleosynthesis signatures
  - important in early galaxy (metal poor stars)
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Magnetohydrodynamic (MHD) SNe

**r-process studies**

- 2D MHD-SNe (and collapsar model)
  - Nishimura et al. 2006, Nishimura et al. 2012
  - Fujimoto, Nishimura, and Hashimoto 2008
- 3D MHD-SNe with neutrino
  - Winteler et al. 2012

**Magnetar**
- strong magnetic field
  $\sim 10^{15}$ G
  ($\sim 1 \%$ of all neutron stars)

**Magneto-driven Supernovae?**
- GRB central engine
- Hypernovae

+ evolution of fast rotator:
  CNO, s-process, enhanced etc.
3D-MHD model with leakage scheme

Winteler et al. (2012) (U. Basel group)

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)
Effects of 3D: hydrodynamical instabilities
jet-like explosion is deformed by Kink instability
Mösta et al., 2014, ApJL

expected ejecta includes neutron-rich matter
- $Y_e \sim 0.1 - 0.2$ with $S \sim 1 - 15 \text{ k}_B$
Modeling of MHD-SNe for r-process studies

· Past works
  · Simplified MHD without detailed micro-physics
  · Collapsar jets (driven by MHD and/or neutrino)

· Recent studies
  · 3D-MHD with simplified “neutrino transport”
  · Strong jet-explosions with strong magnetic fields (see, e.g., Winteler 2012, Mösta 2014)
    → suggests that r-processes occurs

· Open question
  · more weak magnetic fields or slow rotations
  · effects of magneto-rotational instability
r-process in MHD-SNe: “prompt” vs “delayed”

- wide range of B field and rotation
  - SR-MHD in axi-symmetry
  - strong differential rotation (20 Heger 2000)

**prompt-magnetic-jet**
- explodes 20 ms after core-bounce

**delayed-magnetic-jet**
- explodes 72 ms after core-bounce
Ejecta with neutron-rich matter

NN, Takiwaki, Thielemann (in prep.)

green: delayed-jet
red: prompt-jet

$\nu$-absorption are ignored

$\nu$-absorption are ignored
r-process in MHD-SNe: “prompt” vs “delayed”

- **prompt-jet** holds low Ye during collapse and ejection
- **delayed-jet** increases Ye of ejecta during the magnetic fields enhancement via field wrapping
r-process in MHD-SNe: “prompt” vs “delayed”

successful r-process (prompt)  NN, Takiwaki, Thielemann (in prep.)
r-process is suppressed up to second peak (delayed)

![Graph showing abundance vs mass number, with distinct peaks for prompt and delayed processes.](image-url)
r-process result: “weak” $r$-elements

- “weak” r-process pattern (HD122563; Honda 2006)
- contradicted to “universality"

“Honda star”
“weak r-process”?

The difference of explosion (stellar rotation & mag. fields) appears in early galaxy.
### Nucleosynthesis Result: Key Amounts

<table>
<thead>
<tr>
<th></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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<tr>
<td><strong>Type</strong></td>
<td>delayed</td>
<td>prompt</td>
<td>prompt</td>
<td>prompt</td>
<td>prompt</td>
</tr>
<tr>
<td><strong>Ejected Mass</strong></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><strong>R-Proc. Mass</strong></td>
<td>2.68</td>
<td>1.62</td>
<td>3.69</td>
<td>4.05</td>
<td>5.32</td>
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<tr>
<td>(10)</td>
<td></td>
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</tr>
<tr>
<td><strong>56Ni</strong></td>
<td>1.07*</td>
<td>-</td>
<td>0.63*</td>
<td>1.19*</td>
<td>1.21*</td>
</tr>
<tr>
<td>(10)</td>
<td></td>
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</tr>
</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 ($\sim 1\%$ of all supernova, the upper limit)

have impact on chemical evolution/observation
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Weakly magnetized, rapidly rotating progenitors

*Magnetorotational Instability (MRI)*
may be important.

- The MRI occurs magnetized, differentially rotating system.
- The MRI leads to the amplification of the B-field, and angular momentum transfer.

Sawai +13 found the efficient amplification of B-field by global simulations.

This work
- pays attention to the SN dynamics under the occurrence of MRI.
✓ Ideal MHD eqs. are solved ins axisymmetry
✓ Neutrino: Cooling function + Light bulb \((L_{\nu_e}=1 \times 10^{52} \text{ erg/s})\)

**NOTE(by NN): a very simplified treatment**

✓ Progenitor: 15 Msun (Woosley ‘95)
✓ B-field: 3 different strengths, Dipole-like

\[
\begin{align*}
B_{c,\text{in}} &= 5.0 \times 10^{10} \text{ G} \\
&= 1.0 \times 10^{11} \text{ G} \\
&= 2.0 \times 10^{11} \text{ G}
\end{align*}
\]

\[
\Rightarrow B_{\text{PNS}} \sim 10^{13} \text{ G}
\]

✓ Rotation: rapid, differential

\[
(T/W)_{\text{in}} = 0.25 \% \ (\Omega_{\text{in}}=2.7 \ \text{rad/s})
\]

✓ MRI runs with 3 different resolutions

Number of grids

\[
\begin{align*}
\Delta r_{\text{min}} &= 12.5 \text{ m} \ (9250 \times 6400) \\
\Delta r_{\text{min}} &= 25 \text{ m} \ (4700 \times 3200) \\
\Delta r_{\text{min}} &= 50 \text{ m} \ (2500 \times 1600) \\
\Delta r_{\text{min}} &= 100 \text{ m} \ (1200 \times 800)
\end{align*}
\]

\[
\Omega = \Omega_0 \frac{r_0^2}{r_0^2 + r^2}
\]

\(r_0=1000 \text{ km}\)
Plasma beta $p/p_B$  Log[$\beta$]

Strongest B-field

$B_{c,in} = 2.0 \times 10^{11} \text{ G}$

Lowest resolution
MRI unresolved

Weakest B-field

$B_{c,in} = 5.0 \times 10^{10} \text{ G}$

Highest resolution
MRI resolved
non-jet component: neutrino-heating with MRI

heating rate /volume
lower resolution
Sawai & Yamada (2014)
finer resolution

• outflow due to neutrino heating
  • active angular momentum transport by MRI
    (angular momentum transfer $\propto B_{\text{pol}} \times B_{\text{tor}}$)
  • by centrifugal force
• final yields? : needs longer time-scale simulation
Explosion models

Sawai et al. (in prep.)

no MRI

plasma beta $p/p_B$

Log$[\beta]$

resolution

magnetic fields
Neutron-rich ejecta in the Jet-like explosion

$t=325\text{ms (after collapse)}$

$\gamma_e$

km

prompt jet

low entropy ($\approx 10\text{ k}_B/\text{nucleon}$)

abundance

mass number

mass fraction
non-jet ejecta

criterion:
- non-jet component
- radius > 400 km (at 564 ms)
- $Y_e$ must be under estimate (ignored $\nu$-captures)

The peak of $Y_e$ is less neutron-rich
Comparison: jet vs $\nu$-heating (w MRI) ejecta

ejected mass by jet = $2.0 \times 10^{-3}$ $M_\odot$ (only Jet)

**ejecta in jet**

low entropy ($\sim 10$ k$_\text{B}$/nucleon)

**no-jet**

**ejecta in jet**

- mass fraction
- mass number

**no-jet**

- mass fraction
- mass number
MHD-SNe as a source of r-process elements

- r-process on MHD SNe have variation
  - strong jets make heavy r-process,
    weaker jets make “weak” r-process
- NOT main source of the solar abundance
- How much contribute to solar r-process nuclei?
  - each event ejects: $10^{-2} - 10^{-3} \, M_\odot$
    - much mass than proto-NS winds
- Possible observational probe
  - non-solar like abundance pattern
    (cf. HD122563; Honda 2006)
  - more active in low metal stars?