Aspherical Explosion of Massive CO Star

$^{56}\text{Ni}$ production & Hydro-dynamical Effect -

SHINPEI OKITA, HIDEYUKI UMEDA & TAKASHI YOSIDA
Type Ic SN
- Absence of H & He Emission Line
- Core-Collapse Explosion of CO Wolf-Rayet Star

Aspherical Nature

Hypernova: $E_{ex} \sim 10^{52}$ erg

SN1998bw → asymmetrical nature (Maeda&Nomoto 2008)

GRB: Some observational samples associated with SN Ic

<table>
<thead>
<tr>
<th>Name</th>
<th>Redshift</th>
<th>Peak [mag]</th>
<th>$T_{\text{peak}}$ [day]</th>
<th>SN likeness/ designation</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 980425/1998bw</td>
<td>0.0085</td>
<td>$M_V = -19.16 \pm 0.03$</td>
<td>17</td>
<td>Ic-BL</td>
<td>^b</td>
</tr>
<tr>
<td>GRB 031032/2003dh</td>
<td>0.1685</td>
<td>$M_V = -18.80 \pm 0.23$</td>
<td>10 - 13</td>
<td>Ic-BL</td>
<td>^c</td>
</tr>
<tr>
<td>GRB 031123/2003bw</td>
<td>0.1005</td>
<td>$M_V = -19.01 \pm 0.23$</td>
<td>18 - 25</td>
<td>Ibc-BL</td>
<td>^d</td>
</tr>
<tr>
<td>XRF 020903</td>
<td>0.25</td>
<td>$M_V = -18.6 \pm 0.5$</td>
<td>-15</td>
<td>Ic-BL</td>
<td>^e</td>
</tr>
<tr>
<td>GRB 011211/2001dk</td>
<td>0.365</td>
<td>$M_V = -18.5 \pm 0.23$</td>
<td>12 - 14</td>
<td>I (IIn?)</td>
<td>^f</td>
</tr>
<tr>
<td>GRB 050525a</td>
<td>0.606</td>
<td>$M_V \sim -18.8$</td>
<td>12</td>
<td>I</td>
<td>^g</td>
</tr>
<tr>
<td>GRB 021211/2002lt</td>
<td>1.00</td>
<td>$M_V \sim -18.4 \pm 0.23$</td>
<td>-14</td>
<td>Ic</td>
<td>^h</td>
</tr>
<tr>
<td>GRB 970228</td>
<td>0.695</td>
<td>$M_V \sim -19.2$</td>
<td>-17</td>
<td>I</td>
<td>^i</td>
</tr>
<tr>
<td>XRR 041006</td>
<td>0.716</td>
<td>$M_V = -18.8 \pm 0.23$</td>
<td>16 - 20</td>
<td>I</td>
<td>^j</td>
</tr>
<tr>
<td>XRR 040924</td>
<td>0.859</td>
<td>$M_V \sim -17.6$</td>
<td>-11</td>
<td>I</td>
<td>^k</td>
</tr>
<tr>
<td>GRB 020405</td>
<td>0.695</td>
<td>$M_V \sim -18.7$</td>
<td>-17</td>
<td>I</td>
<td>^l</td>
</tr>
</tbody>
</table>
SN2007bi (Gal-Yum+2009)

- Very Luminous Ic SN
- Large amount of $^{56}\text{Ni}$ ($>4\text{M}_{\odot}$)
  $$^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}\) 
- Single peak of observed [OI] emission line does not suggest asphericity
  (Young+2010)

Scenario 1: Pair Instability SN

- PISN of $\sim100\text{M}_{\odot}$ He star
  - Can reproduce the yield
  - He envelope remains

Scenario 2: Core Collapse SN

- Spherical Explosion of $43\text{M}_{\odot}$ CO star
  - $^{56}\text{Ni}$ amount & Light curve evolusion
    (Moriya+2010)
**Progenitor Model**

- $M_{\text{MS}} = 110M_{\odot}, Z=0.004$
- Massive CO Wolf-Rayet star deprived of upto He envelope by mass loss wind
  $\rightarrow M_{\text{CO}} = 43.1M_{\odot}$

**Hydrodynamics**

- Code: 2D axis-symmetric
- Explosion Energy: $E_{\text{ex}} = 30\times10^{51}$ erg
  $^{56}\text{Ni} \sim 4M_{\odot}$
- Inner boundary: absorbing
  Fall-back onto central remnant

**Spherical explosion**

$^{56}\text{Ni}$ is totally ejected if $E_{\text{ex}} > 25\times10^{51}$ erg
**Method 2**

**Aspherical Explosion**
- Induced by abrupt energy injection in polar direction
- 7 models calculated with various opening angle ($\theta_{op}$)

* Explosion energy is injected only around the polar axis as kinetic form

**Nucleosynthesis**
- Post-process
- Network with 282 isotopes ($n,p \sim Br$)

Input: Thermodynamical Histories
{\{\rho_i(t_n), T_i(t_n)\}}
(for every differential mass)

Output: Mass Fraction
{X^j_i} ($\sum_j X^j_i = 1$)

**Thermodynamical Histories**
Trace Particle Method
- 5200 particles ($\Delta m_i \sim 0.001 M_{\odot}$)
- Each particle obtains

<table>
<thead>
<tr>
<th>Name</th>
<th>OA1</th>
<th>OA2</th>
<th>OA3</th>
<th>OA4</th>
<th>OA5</th>
<th>OA6</th>
<th>OA7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{op}$</td>
<td>7.03°</td>
<td>11.3°</td>
<td>22.5°</td>
<td>45.0°</td>
<td>67.5°</td>
<td>78.8°</td>
<td>90.0°</td>
</tr>
<tr>
<td>$\theta_{op}/90°$</td>
<td>5/64</td>
<td>1/8</td>
<td>1/4</td>
<td>1/2</td>
<td>3/4</td>
<td>7/8</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1: Calculated models
Aspherical feature
Aspherical explosion induces large amount of fall-back

Ejected $^{56}\text{Ni}$ or $^{28}\text{Si}$
Steep jump in a certain $\theta_{\text{op}}$ → narrow explosion eject not much $^{56}\text{Ni}$
Simple Evaluation

Large $\theta_{op}$: Valid by $\sim$5%

Small $\theta_{op}$: Photo-dissociation

$\uparrow^{56}\text{Ni} \rightarrow 14^4\text{He}$

Fall-back

$^{56}\text{Ni}$ (isotopes produced around the center): strongly affected by fall-back
OA2
\(\theta_{op}=1/8*90^\circ\)

\[ M(\text{ejec}) = 17.4 \, M_{\text{sun}} \]
\[ M(56\text{Ni}) = 1.77 \, M_{\text{sun}} \]

\[ Z \, [\text{cm}] \]
\[ R \, [\text{cm}] \]

\[ 2M_{\text{sun}} \]
\[ 7M_{\text{sun}} \]
\[ 12M_{\text{sun}} \]

\[ 56\text{Ni} \, \text{only around polar axis} \]

\[ \text{Fall-back from equatorial region} \]

\[ 56\text{Ni \, Accretion Rate} \, [M_{\text{sun}}/\text{sec}] \]

\[ 0 \, \text{to} \, 0.2 \]

\[ 0 \, \text{to} \, 140 \, \text{time [sec]} \]

\[ T=0.1 \, \text{sec} \]
OA4
(θ_op=1/2*90°)

$M(\text{ejec}) = 28.7 \ M_{\odot}$

$M(^{56}\text{Ni}) = 2.42 \ M_{\odot}$

Ejected $^{56}$Ni is spatially confined.

56Ni Accretion Rate [M_{\odot}/sec]
$\text{OA5}$  
$(\theta_\text{op}=3/4 \times 90^\circ)$

$M(\text{ejec}) = 36.8 \, M_\odot$

$M(^{56}\text{Ni}) = 2.47 \, M_\odot$

- Central configuration does not change so much.
- Accretion region becomes small.

$^{56}\text{Ni}$ accreted.

$^{56}\text{Ni}$ Accretion Rate $[M_\odot/\text{sec}]$

$\rightarrow$ Delayed accretion $\sim 10 \, \text{sec}$
Ejected Mass [$M_{\text{sun}}$]

$^{56}\text{Ni}$, $^{28}\text{Si}$, $^{16}\text{O}$

Ejecta

Opening Angle

Fall-back/Produced $^{56}\text{Ni}$

Ejected $^{56}\text{Ni}$

(post-process) Ejected $^{56}\text{Ni}$

Fall-back/Produced $^{56}\text{Ni}$
OA6
(θ_{op}=7/8*90°)

M(ejec) = 40.2 \, M_{\odot}
M(^{56}\text{Ni}) = 4.01 \, M_{\odot}

Pretty small accretion region

56\text{Ni}
other

Loss of initial accretion
\[ M(\text{ejec}) = 28.7 \ M_{\text{sun}} \]
\[ M^{(56}\text{Ni}) = 2.42 \ M_{\text{sun}} \]

\[ M(\text{ejec}) = 36.8 \ M_{\text{sun}} \]
\[ M^{(56}\text{Ni}) = 2.47 \ M_{\text{sun}} \]

\[ M(\text{ejec}) = 40.2 \ M_{\text{sun}} \]
\[ M^{(56}\text{Ni}) = 4.01 \ M_{\text{sun}} \]
Chemical Abundance Ejected by Aspherical Explosion of Massive CO Star

- **Aspherical Effect**: Ejecta decreases towards small $\theta_{op}$
- Isotopes produced around the center suffer from Fall-back or Hydro-dynamical Effect according to $\theta_{op}$
- $^{56}$Ni is ejected more than $4M_{\odot}$ if $\theta_{op}/90^\circ \geq 7/8$
  $\rightarrow$ Observed sphericity of SN2007bi is not accidental