Type Ibc Supernovae and GRBs

Paolo A. Mazzali

Max-Planck Institut für Astrophysik, Garching

INAF, OA Padova & Scuola Normale Superiore, Pisa

Astronomy Department and RESearch Centre for the Early Universe, University of Tokyo
Gamma-Ray Bursts

GRBs are brief flashes of soft $\gamma$-ray radiation ($\sim 100$ keV), discovered in the 1960-70’s, whose origin was still unknown 10 years ago.
Isotropic distribution: extragalactic origin

2704 BATSE Gamma-Ray Bursts

Fluence, 50-300 keV (ergs cm$^{-2}$)
GRB Duration:
Bimodal distribution

The progenitors of short bursts are probably binary neutron stars or neutron star-black hole binaries.
**Type Iabc Spectra**

- **SN Ic**: no H, no strong He, no strong Si

- **Hypernovae**: broad features, blended lines

  "Large mass at high velocities"

---

4.6.2009 KIAA, Beidai
Core-Collapse SNe

Massive Star (>8M\(_\odot\))

- Si burning \(\rightarrow\) NSE \(\rightarrow\) \(^{56}\)Ni (~0.1-1M\(_\odot\))
- Core collapse
- Compact object (NS/BH)
- \(v\) emission
- KE deposited
- envelope ejection
GRB980425: the optical counterpart

4.6.2009 KIAA, Beidai
The Type Ic SN 1998bw

SN1998bw was a very bright Type Ic SN, with very broad absorption lines, indicative of high-velocity ejecta (~0.1c), and of a very energetic explosion.
Type Ic SNe / Hypernovae

Broad lines
→ Large Kinetic Energy
→ “Hypernovae”
(only SN1998bw was associated with a GRB)

Narrow lines
→ “normal” KE (1 foe)
→ Normal SN Ic

Mazzali et al. 2002
A very bright SN

- SN1998bw made much more 56Ni than ‘normal’ core-collapse SNe

- It was as bright as a SN Ia
Explosion Parameters

\( M_{ej}, M(^{56}Ni), KE \)

\[ \tau_{LC} \sim \left( \tau_{dyn} \cdot \tau_{diff} \right)^{1/2} \]
\[ \sim \left( \frac{R}{V} \frac{\kappa M_{ej}}{R c} \right)^{1/2} \]
\[ \tau_{LC} \propto \frac{\kappa^{1/2} M_{ej}^{3/4}}{E^{1/4}} \]

\[ \nu_{ph} \propto \left( \frac{E}{M_{ej}} \right)^{1/2} \]
Early-time spectrum

- Ejecta are dense
  “Photospheric Epoch”

\[ L = 4\pi R_{ph}^2 \sigma T_*^4 \]

\[ R_{ph} = \nu_{ph} t \]
Early-time spectrum

- Lines have P-Cygni profiles with
  \[ V_{abs} \sim V_{ph} \]

But velocities are high: many lines overlap:
“Line Blanketing”
A “typical” (?) SN Ic: SN1994I

- Fit spectrum with a classical model:
- $\text{Mej} \sim 1 \text{ M}\odot$, $\text{KE} \sim 10^{51} \text{ erg (1 foe)}$
- Abundances dominated by O, Si
- $M(^{56}\text{Ni}) \sim 0.1 \text{ M}\odot$

Sauer et al. 2006
`Classic’ SN Ic vs. `Hypernova’ model

Slow light curve

→ massive ejecta

Model CO60 (1 foe):

\[ M(CO) = 6M_\odot \]

Model CO110 (8 foe):

\[ M(CO) = 10M_\odot \]

both:

\[ M(56Ni) = 0.15M_\odot \]

SN 1997ef

Iwamoto et al. 2000
A broad-lined SN Ic: SN1997ef
early-time spectra
A classical model:
Model CO60
KE = 1 foe,
Mej = 6 M☉
Too little mass at high velocity

Iwamoto et al. 2000
SN 1997ef
early-time spectra
A hypernova model: CO100
KE = 20 foe
Mej = 8 M☉

Mazzali et al. 2000

4.6.2009 KIAA, Beidai
Determining the properties of SN 1998bw

Light curves can be degenerate if both M and E are allowed to vary

\[ \tau_{LC} \propto \frac{\kappa^{1/2} M^{3/4}}{E^{1/4}} \]

Iwamoto et al. 1998

Iwamoto et al. (1998)

D = 38 Mpc
E(B-V) = 0.05
0.7 \, M_{\odot}^{56}\text{Ni}

\[ ^{56}\text{Co decay} \]

4.6.2009 KIAA, Beidai
SN 1998bw

Early-time spectra

Model CO138

\[ KE = 5 \times 10^{52} \text{erg} \]

\[ M_{ej} = 10.9 M_\odot \]

4.6.2009

KIAA, Beidai

Iwamoto et al. 1998
Late-time spectra

Ejecta are thin:
“Nebular Epoch”
Gas heated by deposition of γ’s and e^+
cooled by forbidden line emission

Spectrum: no continuum.
Emission line profiles depend on velocity,
abundance distribution:
explore inner part of SN.
Homologous expansion, homogenous density and abundance:
parabolic profiles
SN 1998bw

Late-time spectra

`Broad-line’ models

$v \approx 10,000 \text{ km/s}$

$M(^{56}\text{Ni}) \sim 0.6 M_\odot$

Fits Fell lines

4.6.2009

KIAA, Beidai

Mazzali et al. 2001
SN 1998bw
Late-time spectra
`narrow-line’ models

\( v \approx 6,000 \text{ km/s} \)

\[ M^{(56}\text{Ni}) \approx 0.35 M_\odot \]

Fits OI line

Mazzali et al. 2001

4.6.2009 KIAA, Beidai
Late time spectra of SN1998bw

Fe lines broader than O lines

[FeII] 5200A  [OI] 6300A

Observation

Expansion

Observer

Never in Spherical Model

Maeda et al. 2002
Interpretation as an Aspherical explosion

1.0 \times 10^3
0
0
5 \times 10^3
1.0 \times 10^3
2 \times 10^3

\begin{align*}
\text{Fe}^{56} & \quad 16O
\end{align*}

5200A

[O I] 6300A

Spherical

Aspherical

Orientation 15 deg

4.6.2009 KIAA, Beidai

Maeda et al. 2002
Indications that explosion was asymmetric

**Link to GRB’s**

Baron 1998
Bumps in GRB LCs: SNe?

Garnavich et al. 2003
The Confirmation:

**GRB030329 / SN2003dh (HN)**

\[ Z = 0.167 \]

Stanek et al. 2003

**4.6.2009**

KIAA, Beidai
SN 2003dh: the light curve

SN 2003dh is somewhat dimmer than SN 1988bw, but much brighter than both SNe 1997ef and 2002ap

Mazzali et al. 2003
SN 2003dh: another Hypernova

SN 2003dh is almost as bright and powerful as SN 1998bw:

KE = $3.8 \times 10^{52}$ erg

$M(^{56}Ni) \sim 0.35M_\odot$

$M_{ej} \sim 8M_\odot$

Mazzali et al. 2003
SN2003dh: the nebular phase

The nebular spectrum shows a strong but narrow [O I]6300 line, like SN1998bw.

Model:
\[ v = 5000 \text{ km/s} \]
\[ M(^{56}Ni) \sim 0.35 M_\odot \]
The Nail in the Coffin:
GRB031203 / SN2003lw (HN)

z = 0.105

Highly reddened, but a close analogue of SN1998bw

With GRB031203/SN2003lw, ALL 3 nearest GRBs are Hypernovae

Malesani et al. 2004
A low-mass HN w/o a GRB: SN2002ap in M74
SN Ic 2002ap in M74 another GRB-less HN
SN2002ap: modelling the light curve

Model CO100/4

KE = 4 foe

\[ M_{ej} = 2.5 M_\odot \]

\[ M(^{56}\text{Ni}) \sim 0.07 M_\odot \]

Mazzali et al. 2002
SN 2002ap: early spectral models

Model CO100/4

Mazzali et al 2002
SN 2002ap: nebular models

Foley et al. 2003

$M(^{56}\text{Ni}) = 0.10 \, M_\odot$

4.6.2009
KIAA, Beidai
SN 2002ap: a “mini” HN...

- $M_{\text{ejecta}} \sim 2.5 M_\odot - 5 M_\odot$
- $M(^{56}\text{Ni}) \sim 0.07-0.1 M_\odot$
- KE $\sim 4 - 10$ foe

- $M_{\text{ZAMS}} \sim 20 - 25 M_\odot$
  - SN/HN Boundary?
- $M_{\text{REM}} > 2 M_\odot$
  - BH/NS Boundary

- Matter Mixing
  - He: Outer Layer $\Rightarrow$ Mixed In.
  - $^{56}\text{Ni}$: Deepest Region $\Rightarrow$ Surface.
    (He coexists with O, Rapid Rise in LC)

4.6.2009 KIAA, Beidai
• 3 nearby GRBs are HNe

• Some (less energetic) HNe show no GRB → Viewing angle effect or real?

• XRFs may host low-E HNe

• Are XRF/SNe GRB/HNe viewed off-axis, or just weaker explosions?
Rates of GRBs and HNe

**GRBs:**

- Observed: \( R_{\text{obs}} = 10^{-7} \text{ yr}^{-1} \)
- Beaming factor: \( 2\Omega/4\pi \)

\((\sim 10^{-2} \text{ for jet opening})\)

\( \Rightarrow R(\text{GRB}) \sim 10^{-5} \text{ yr}^{-1} \)

**HNe:**

- C C SNe: \( 7 \times 10^{-3} \text{ yr}^{-1} \)
- of these, SNe Ib/c: \( 10^{-3} \text{ yr}^{-1} \)
- HNe: 5\% of SNe Ib/c, but 3-5 \times brighter

\( \Rightarrow R(\text{HNe}) \sim 10^{-5} \text{ yr}^{-1} \)

These are lower than rate of SNe from massive stars:

\[
R(\text{SN}; M > 80M_\odot) = 2 \times 10^{-4} \text{ yr}^{-1}
\]

Podsiadlowski et al. 2004
[O I] line profiles as tracers of Asphericity

- GRB/SNe show [O I] line narrower than [Fe II] lines
  ➔ aspherical explosions viewed near the axis of energy injection
  (in agreement with presence of GRBs)
- Lower energy, non-GRB/SNe do not share this.

- Are GRB/SNe the only aspherical SNe Ic?
  - No: normal SNe Ic are polarised
- GRB/SNe may be the most aspherical SNe
- What is the effect of the viewing angle?
  ➔ looking for asphericity through late-time spectra: a Subaru-VLT campaign

4.6.2009 KIAA, Beidai
The bright Type Ic SN 2003jd
The bright Type Ic SN 2003jd

- SN 2003jd was as bright at peak as SN1998bw (Mv = -18.7)
- Early-time spectra had broad lines, similar to HN SN2002ap
- No GRB or XRF

Mazzali et al. (2005)
SN 2003jd: an aspherical SN viewed off-axis

- The [O I] 6300A line shows a double peak, suggesting an explosion similar to SN1998bw but viewed ~70° from the axis

(Subaru and Keck data, Mazzali et al. 2005)
What we see depends on where we look…

Mazzali et al. (2005)
Was SN 2003jd also a GRB/HN?

- X-ray and Early Radio upper limits are not in contradiction with a GRB viewed off-axis
- Later Radio upper limits (Soderberg et al 2005) indicate no jet

4.6.2009 KIAA, Beidai

Mazzali et al. 2005
Radio Properties of SNe Ibc

Most HNe show no radio (Soderberg et al 2005)

Either no jet, or a low-density environment (wind)

4.6.2009 KIAA, Beidai
A puzzle…

- GRB/SNe are SNe Ic, most likely HNe
- HNe in GRBs have radio
- Off-axis HNe show no radio…

1) Do all HNe make GRBs?
2) Where are the off-axis GRBs?
3) What are the jet properties of HNe (is there a jet at all)?
A SN in XRF030723?

XRFs are the weak (X-ray dominated) analog of GRBs

Bump in LC interpreted as a SN

LC Fits: a normal SN Ic or a low-E HN like SN2002ap at z~0.6

Fynbo et al. 2004

Tominaga et al. 2004
GRB (XRF) 060218

- X-ray Flashes (XRFs) are the weak (X-ray dominated) analogues of GRBs
- Detected on February 18.149 UT by BAT on board SWIFT
- XRF was on when BAT slewed to position
- The event was long (rise 900 s, exp dec 2100s), weak, soft ($E_{pk} = 5$KeV) → XRF, shallow (power-law index n=2.5)
- bright, long (10hr), steady UV counterpart
XRF060218/SN2006aj

VLT images

4.6.2009
SN2006aj: Bolometric Light Curve

SN2006aj was dimmer than other GRB/SNe (98bw, 03dh, 03lw)

Light curve similar to non-GRB broad-lined SN Ic 2002ap, but brighter

Estimate $\sim 0.2 M_\odot$ of $^{56}\text{Ni}$

Rapid LC evolution: $\Rightarrow Mej^3/E$ is small
VLT (& Lick) Spectra

Relatively broad lines, but not as broad as in GRB/HNe (Pian et al. 2006)
An Oxygen-poor SN Ic (Ic/d?)

Closest match is the broad-lined, non-GRB SN2002ap, more than the "traditional" HN SN1998bw.

O line (7300Å) weak or absent.
Spectral modelling

Model similar to that used for SN2002ap, but with smaller $M_{ej}$, KE, more $^{56}$Ni, less O.

O-dominated shell ($\sim 0.1M_\odot$) at 20-25,000 km/s: shell ejection from progenitor?

$$M_{ej} \sim 2M_\odot$$

$$M(^{56}Ni) \sim 0.21M_\odot$$

$$E_K \sim 2 \times 10^{51} \text{ erg}$$

Mazzali et al 2006, Nature
Evolution of photospheric velocity from spectral modelling

- SN2006aj never reached velocities as high as the GRB/SNe
- It is intermediate between non-GRB, broad-lined SNe Ic such as SN2002ap and SN1997ef, and GRB/SNe

Pian et al. 2006, Nature
SN 2006aj: Light Curve model

Explosion model gives a LC consistent with results of spectral fitting.

The progenitor was a small mass star ($M_{\text{ZAMS}} \sim 20 \, M_\odot$).

A NS ($M \sim 1.4 \, M_\odot$) was formed.
Placing SN2006aj in context

A neutron star-making SN

4.6.2009 KIAA, Beidai
# Properties of Type Ib/c Super/Hypernovae

<table>
<thead>
<tr>
<th>SN type</th>
<th>83N</th>
<th>94I</th>
<th>06aj</th>
<th>02ap</th>
<th>97ef/dq</th>
<th>98bw</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>Ib</td>
<td>Ic</td>
<td>Ic-en</td>
<td>Ic (Hypernovae)</td>
<td>Ic (Hypernovae)</td>
<td>Ic (Hypernovae)</td>
</tr>
<tr>
<td>$M_{ZAMS}$</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>21</td>
<td>34</td>
<td>40</td>
</tr>
<tr>
<td>$M_{He}$</td>
<td>4</td>
<td>4</td>
<td>5.5</td>
<td>6.6</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>$M_{CO}$</td>
<td>2</td>
<td>2</td>
<td>3.3</td>
<td>4.5</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>$M_{Expl}$</td>
<td>4</td>
<td>2.1</td>
<td>3.3</td>
<td>4.6</td>
<td>11.1</td>
<td>13.8</td>
</tr>
<tr>
<td>$M_{Rem}$</td>
<td>1.25</td>
<td>1.2</td>
<td>1.4 NS</td>
<td>2.1</td>
<td>1.6</td>
<td>2.9</td>
</tr>
<tr>
<td>$M_{Ej}$</td>
<td>2.75</td>
<td>0.9</td>
<td>2.0</td>
<td>2.5</td>
<td>9.5</td>
<td>10.9</td>
</tr>
<tr>
<td>$M_{He}$</td>
<td>2.0</td>
<td>---</td>
<td>---</td>
<td>0.1</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$M_{CO}$</td>
<td>0.5</td>
<td>0.6</td>
<td>1.4</td>
<td>1.8</td>
<td>5.3</td>
<td>8</td>
</tr>
<tr>
<td>$M_{IME(Si,S)}$</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
<td>0.5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>$M_{Ni}$</td>
<td>0.15</td>
<td>0.07</td>
<td>0.2</td>
<td>0.1</td>
<td>0.13</td>
<td>0.7</td>
</tr>
<tr>
<td>$E_{51}$</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>19</td>
<td>50</td>
</tr>
<tr>
<td>GRB</td>
<td>X</td>
<td>X</td>
<td>√ (XRF)</td>
<td>X</td>
<td>X</td>
<td>√</td>
</tr>
</tbody>
</table>
SN2006aj in the nebular phase

- Not as aspherical as SNe 1998bw, 2003jd.
- Closer to SN 2002ap

4.6.2009

KIAA, Beidai
Properties of SN2006aj

- SN 2006aj exploded as a CO core (a WR star) of \( \sim 3.3 \, M_\odot \).
- The ejecta (\( \sim 2M_\odot \)) consisted of O (\( \sim 1.3M_\odot \)), and heavier elements (\( \sim 0.6M_\odot \)), incl. \( \sim 0.2M_\odot \) of \(^{56}\text{Ni}\).
- Explosion not highly aspherical
- A NS (M \( \sim 1.4 \, M_\odot \)) was formed.

\[ \Rightarrow \text{The progenitor of SN 2006aj was a small mass star (M}_{ZAMS} \sim 20 \, M_\odot). \]
Role of Magnetar

- Magnetar activity may have been responsible for the high energy transient
- possible rebrightenings (as in SN2005bf, Maeda et al. 2007)
All SNe Ibc consistent with mildly aspherical explosions

Maeda et al. 2008, Science
What happens in SNe Ib?

SN2008D: breakout

X-rays  optical  IR

4.6.2009

KIAA, Beidai
Light curve

- First peak observed, as seen in only a few other cases
- interpreted as shock breakout from a normal SN Ib
- But is SN 2008D normal?
A Type Ib Hypernova

- Fits indicate a highly energetic ($E \sim 7 \times 10^{51}$ erg) SN Ib, which ejected $\sim 6 \, M_\odot$ of material:
  - Not a normal SN
  - Progenitor $\sim 25-30 \, M_\odot$
  - Remnant: Black Hole
  - XRF was the breakout of a failed jet, born weak or choked by He envelope
  - SN2008D connects GRB/SNeIc and massive, energetic SNe Ib

Mazzali et al. 2008, Science
Props of SNe Ibc as f(prog. mass)
Nebular spectra

- [O I] line has double-peaked profile, like SN2003jd
- An energetic, highly aspherical explosion, viewed far from the polar axis
The Grand Scheme

• Collapse of very massive (~35-50 M\(\odot\)), stripped stars to BHs makes aspherical GRB-HN (GRB can be very different, HN much less).

• Collapse of less massive star (~ 20 M\(\odot\)) to NS can cause an XRF (via magnetic activity ?).

• Some of these NS may later (when spin is lower) harbour some short-hard GRBs (SGRs).

• If system is a close binary (possibly necessary for mass loss) it may end as a NS-NS merger and again produce a short-hard GRB.
Conclusions/Present status

• Very massive stars (>25M☉) collapsing to BHs launch GRBs and are accompanied by a Hypernova (energetic, aspherical)
• Less massive stars collapsing to NS’s cause a less aspherical and energetic SN, and may be accompanied by XRFs if a Magnetar is born
• All SNe Ibc will have shock breakout
• If star collapses as He core, jet can be choked and breakout and jet may both be relevant
Debates

• What do off-axis GRBs look like?
• Are all GRBs similar (viewing angle effect) or are they really very different?
• How do GRBs and XRF relate?
• Role of binarity for progenitor evolution?
• ….. Cosmological use….???