Hypernovae, GRBs, CasA: a connection?

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15.1.09 CasA and HNe
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.
The progenitors of short bursts are probably binary neutron stars or neutron star-black hole binaries.
GRB980425: the optical counterpart
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
Light curves can be degenerate if both $M$ and $E$ are allowed to vary

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

Iwamoto et al. 1998

SN 1998bw

Iwamota et al. 1998
SN 1998bw

Early-time spectra

Model CO138

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

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

Iwamoto et al. 1998
SN 1998bw

Late-time spectra

`Broad-line’ models

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

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

Fits Fell lines

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Mazzali et al. 2001
Late time spectra of SN1998bw

Fe lines broader than O lines

[FeII] 5200Å
[OI] 6300Å

Observation

Never in Spherical Model

Maeda et al. 2002
Interpretation as an Aspherical explosion

Spherical

FeII] 5200Å
[OI] 6300Å

Aspherical

Orientation 15 deg

Maeda et al. 2002

56Fe
16O

Observed

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[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
The bright Type Ic SN 2003jd
The bright Type Ic SN 2003jd

- SN 2003jd was as bright at peak as SN1998bw ($M_V = -18.7$)
- 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, Science)
XRF060218/SN2006aj

X-ray Flashes (XRFs) are the weak (X-ray dominated) analogues of GRBs.
SN2006aj was dimmer than other GRB/SNe (98bw, 03dh, 03lw)

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

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

Rapid LC evolution: $\Rightarrow Mej^3/E$ is small
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
SN2006aj in the nebular phase

- Not as aspherical as SNe 1998bw, 2003jd
Properties of SN2006aj

• SN 2006aj exploded as a CO core (a WR star) of ~3.3 M☉.
• The ejecta (~2M☉) consisted of O (~1.3M☉), and heavier elements (~ 0.6M☉), incl. ~ 0.2M☉ of ⁵⁶Ni.
• Explosion not highly aspherical
• A NS (M ~ 1.4 M☉) was formed.
• High energy and ⁵⁶Ni caused by Magnetar
→ The progenitor of SN 2006aj was a small mass star (M_{ZAMS} ~ 20 M☉).
M(^{56}\text{Ni}), E_k, depend on M_{\text{ZAMS}}
The Grand Scheme

• Collapse of very massive (~35-50 M⊙), stripped stars to Black hole makes GRB-HN (GRB can be very different, HN much less).

• Collapse of less massive star (~ 20 M⊙) 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.
Cassiopeia A

Youngest known galactic SNR.
Well studied at all energies.
D = 3.4 kpc, explosion 1680 AD, forward shock speed 5000-6000 km/s, radius = 2.5 pc.
Ratio forward/reverse shock radii = 1.5 – 1.8 (i.e. varies).

Mej~2M☉; Ek~2 \times 10^{51}\text{erg}

Ejecta dominate X-ray emission in Cas A, often appear in knots.

courtesy M. Laming

1 Ms Chandra Image

red - He-like Si,
blue – He-like Fe,
green – continuum 4-6 keV
$^{44}$Ti Detections in Cassiopeia A

Iyudin et al. (1997; Comptel) $3.3+/-.0.6 \text{ e}-5 \text{ cts/cm}^2\text{s}$

Vink et al. (2001; BeppoSAX) $1.9+/-.0.9 \text{ e}-5 \text{ cts/cm}^2\text{s}$

$M(^{44}\text{Ti}) \sim 1.3 \times 10^{-4} \text{ M}\odot$ (Rothschild & Lingenfelter 2003)
Spectral Analysis

3 Radial Series of O rich Knots

Radial series of knots in Cas A and typical spectrum. Si, S, Ar, Ca lines and O continuum dominate.
Fe knots and clouds

Positions of Fe knots (o) and diffuse cloud (box) on E limb.

Almost pure Fe emission. Fe/Si=12 solar. Did alpha-rich freeze-out occur here?
Spectrum of Fe rich knots, local bkgd subtracted, fit with Si, S, Ar, Ca, Fe.

*Fe/Si=*2.7 solar by number,

*n_et*=$7 \times 10^{11}$ s/cm$^3$

*kT*=$1.6$ keV

Looks like explosive Si burning
Jet Models

- Self similar model from Truelove & McKee (1999) with $\rho_{ej} \sim r^{-1}$.
- Equiv. sph. $M_{ej} \sim 1.8 M_\odot$
- Equiv. iso. $E_k = 2.3 \times 10^{52}$ ergs.
- Total jet $E_k \sim 10^{50}$ ergs for jet opening angle of 7°. Too small to have actually been a GRB, by at least an order of mag.
- Likely a SN IIb (some H, He)
- Progenitor was less massive than SN2006aj/XRF060218: $M(ZAMS) \sim 17-18 M_\odot$
- Could have been an XRF?: $E_{\gamma, iso(06aj)} \sim 6 \times 10^{49}$ erg