The GRB-Supernova Connection

Li-Xin Li (MPA/KIAA)
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Gamma-Ray Bursts (GRBs)
Short and intense pulses of soft gamma-rays.

- **Duration**: $T = 10\text{ms} - 1000\text{s}$
- **Spectrum**: non-thermal, broad band (radio – gamma)
- **Peak Luminosity**: $10^{50} - 10^{53} \text{erg/s}$
- **Isotropic Energy**: $10^{50} - 10^{54} \text{erg}$
- **Distribution**: isotropic on the sky
- **Distance**: cosmological distance (highest known $z = 6.3$)
- **GRBs are relativistic**: $v \sim c, \Gamma > 100$

GRBs are the most powerful explosions since the Big Bang. They are very useful for probing cosmology.
Classification of GRBs

GRBs are often classified by their durations

Long (soft) GRBs: \( T > 2\text{s} \)
Short (hard) GRBs: \( T < 2\text{s} \)

(Paciesas et al 1999) (Qin et al 2000)
Models of GRBs

Long GRBs: the Collapsar Model

The iron core of a rapidly rotating massive star (> 30 Msun) collapses to a black hole. An accretion disk forms around the BH. Two oppositely directed jets, powered either by the disk accretion or the BH's spin energy, produce long GRBs.

Observational evidence:

- Long GRBs are always found in star-forming galaxies.
- Some long GRBs are associated with core-collapse supernovae.

Short GRBs: Merger of Neutron Stars

Short GRBs are found in both star-forming and non-star-forming galaxies, and are not associated with SNe.
Supernovae (SNe)
Stellar explosion at the end of a star's life.

- **Duration:** years – centuries (remnants)
- **Peak luminosity:** up to $10^{43}$ erg/s.
  Intrinsically $10^{10}$ times brighter than Sun, $10^{10}$ times fainter than GRBs.
- **Energy:** kinetic $\sim 10^{51}$ erg; radioactive decay $\sim 10^{49}$ erg;
  neutrino (GW) $\sim 10^{53}$ erg
- **SNe are usually nonrelativistic.** In extreme case: $v \sim 0.3 \, c$
- **Distance:** noncosmological distance ($z < 1$)

Observations of SNe have a much longer history than that of GRBs. Hence, our understanding of SNe is much better than that of GRBs.

Crab Nebula (SN 1054)
**SNe Classification**

SNe are generally classified by their spectra

Type I – have no hydrogen line
   Ia – have silicon lines
   Ib – no silicon line but have helium lines
   Ic – no silicon, weak or no helium

Type II – have hydrogen lines

**Progenitors of SNe**

Type Ia (most luminous SNe): Thermal nuclear explosion of white dwarfs

Type Ib, Ic, and II: Core collapse of massive stars

So, Type Ibc and II SNe are called Core-Collapse SNe
GRB 980425/SN 1998bw: They Are Associated!

The GRB:
Detected by BATSE/BeppoSAX
Single pulse, duration = 35 s
Nearest GRB, z = 0.0085
Very faint: at least $10^4$ times fainter than normal GRBs.

The SN:
Discovered in the error box of the GRB, 2.5 days after the GRB. One of the most unusual Type Ic SNe ever seen. Very bright – comparable to a Type Ia; strong radio emission – indicating relativistic expansion ($v \sim 0.3 \, c$).

(Galama et al 1998; Kulkarni et al 1998)
The GRB-SN Connection

So far four pairs of GRBs-SNe with spectroscopically confirmed connection have been found:

- GRB 980425 / SN 1998bw: $z = 0.0085$
- GRB 030329 / SN 2003dh: $z = 0.1687$
- GRB 031203 / SN 2003lw: $z = 0.1055$
- GRB 060218 / SN 2006aj: $z = 0.0335$

GRB-SNe are among a special class of Type Ic: broad-lined SNe, characterized by relative smooth spectra and a very large explosion energy.

So, they are often called 'hypernovae'.

Modjaz et al. 2006
It appears that SN 2006aj is closer to normal Type Ibc SNe than to GRB-SNe.


$\left( \Omega_m = 0.28, \Omega_\Lambda = 0.72, H_0 = 73 \right)$
Correlation between the GRB Peak Energy and the SN Maximum Luminosity (Li 2006)

The Pearson linear correlation coefficient

\[ r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} = 0.997 \]

corresponding to \( P = 0.003 \) for zero correlation.

\[ E_{\gamma, \text{peak}} = 90.2 \text{ keV} \left( \frac{L_{\text{SN, peak}}}{10^{43} \text{ erg/s}} \right)^{4.97} \]

\( (\Omega_m = 0.28, \Omega_\Lambda = 0.72, H_0 = 72) \)

Constraint on the GRB Isotropic Energy

Amati (2006):

\[ E_{\gamma, \text{peak}} = 97 \text{ keV} \left( \frac{E_{\gamma, \text{iso}}}{10^{52} \text{ erg}} \right)^{0.49} \]

Some GRBs have energy smaller than that predicted by the Amati relation (980425, 031203, and short GRBs).

Hence, we have (Li 2006)

\[ E_{\gamma, \text{iso}} \leq 0.86 \times 10^{52} \text{ erg} \left( \frac{L_{\text{SN, peak}}}{10^{43} \text{ erg s}^{-1}} \right)^{10} \]
GRB 060218/SN 2006aj
Detected by BAT/Swift

The GRB:
Very faint, duration ~ 2000 s
The 2\textsuperscript{nd} nearest GRB, \( z = 0.0335 \)

XRT & UVOT started observing it 156s after trigger

The SN:
Discovered 3 days after the GRB. It is intrinsically less luminous than other GRB-SNe, but more luminous than normal SNe Ibc. (Modjaz et al '06; Pian et al '06; Sollerman et al '06)

The discovery of GRB 060218 / SN 2006aj has put the GRB-SN connection on a solid foundation
GRB 060218/SN 2006aj

Black-body

\[ T_{BB} \approx 0.17 \text{ keV} \]

\[ E_{BB} \approx 10^{49} \text{ erg} \]

It occupies 20\% of total emission, lasting up to 10000 s

Campana et al. interpreted it as SN shock breakout from the progenitor Wolf-Rayet star.

Campana et al. 2006, Nature, 442, 1008

Supernova
However, detailed calculations show that the blackbody in GRB 060218 cannot be due to the SN shock breakout, unless the progenitor Wolf-Rayet star has an unrealistically large radius > 100 Rsun! (Li 2007, MNRAS, 375, 240)

\[ R_{\text{star}} = 1 - 100 \, R_{\text{sun}} \]
Correlation between the peak spectral energy of gamma-ray bursts and the peak luminosity of the underlying supernovae: implication for the nature of the gamma-ray burst–supernova connection

Li-Xin Li
Max-Planck-Institut für Astrophysik, 85741 Garching, Germany

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ABSTRACT
In this paper, we present a correlation between the peak spectral energy of gamma-ray bursts (GRBs) and the peak bolometric luminosity of the underlying supernovae (SNe), based on a sample of four pairs of GRBs–SNe with a spectroscopically confirmed connection. Combining it with the well-known relation between the peak spectral energy and the isotropic equivalent energy of GRBs, we obtain an upper limit on the isotropic energy of GRBs, which is \( \approx 10^{52} \text{ erg} (L_{\text{SN,peak}}/10^{43} \text{ erg s}^{-1})^{10} \), where \( L_{\text{SN,peak}} \) is the peak bolometric luminosity of the SNe. Our results suggest that the critical parameter determining the GRB–SN connection is the peak luminosity of SNe, rather than the feature of the SN spectra and/or the SN explosion energy as commonly hypothesized. Because it is generally believed that the peak luminosity of SNe powered by radioactive decays is related to the amount of \(^{56}\text{Ni}\) produced in the SN explosion, the mass of \(^{56}\text{Ni}\) may be a key physical factor for understanding the nature of GRBs and their connection with SNe. Application of our relation to Type Ibc SNe with normal peak luminosities indicates that, if those normal SNe have GRBs accompanying them, the GRBs would be extremely soft and subenergetic in gamma-rays and, hence, easier to detect with X-ray or UV detectors than with gamma-ray detectors.

Key words: supernovae: general – gamma-rays: bursts.
On 9 Jan 2008: a bright X-ray transient was discovered in NGC 2770, during a follow-up observation of SN 2007uy by XRT/Swift (Soderberg et al. '08; Modjaz et al. '08)

- Lightcurve: FRED shape. Duration: ~600 s
- Distance: $z = 0.006494$, $D = 29$ Mpc
- Luminosity: $2 \times 10^{43}$ erg/s in 0.3-10 keV
- At the same position, a Type Ib SN 2008D was found later
Transient 080109 is an X-Ray Flash associated with a normal core-collapse supernova


It satisfies the Amati Eiso-Epeak relation:

Eiso = 1.3e+46 erg;  
XRT+UVOT data leads to  
0.037 keV < Epeak < 0.3 keV.

(SN shock breakout interpretation has also been proposed: Soderberg et al. '08; Chevalier & Fransson et al. '08)
XRF 080109/SN 2008D satisfy the relation between $E_{\text{peak}}$ of GRBs and $L_{\text{peak}}$ (or the mass of Ni) of the underlying SNe.

Li 2008, arXiv:0803.0079
SUMMARY

So far, we have discovered five pairs of GRBs (XRFs) and SNe with spectroscopically confirmed connection:

- GRB 980425 / SN 1998bw: $z = 0.0085$
- GRB 030329 / SN 2003dh: $z = 0.1687$
- GRB 031203 / SN 2003lw: $z = 0.1055$
- GRB 060218 / SN 2006aj: $z = 0.0335$
- XRF 080109 / SN 2008D: $z = 0.006494$

There appears to be a relation between the GRB/XRF peak spectral energy and the SN peak luminosity (Nickel mass).
CAUTIONS

1. Although it has been suggested that all long-duration GRBs are associated with SNe (Zeh et al. 2004), some nearby long GRBs have not been found to have SNe (e.g., GRBs 060505 at $z=0.089$, and 060614 at $z=0.125$).

2. It might be that not all core-collapse SNe are associated with GRBs/XRFs. E.g., the broad-lined Type Ic SN 2003jd (at $z=0.01886$) is only slightly less luminous than 1998bw but no GRB/XRF has been found to be with it.
Future Prospects

- Looking for more GRB-SN pairs
- SN shock breakout remains to be discovered/confirmed

**GLAST:** NASA's major mission dedicated to observations of the gamma-ray universe, including GRBs. Broad range of energy: 5 keV-300 GeV (GBM+LAT). (Launched in 11 June 2008.)

**ECLAIRS/SVOM:** joined French-Chinese mission. A multi-wavelength observatory. Particularly suitable for GRBs-SNe, and possibly SN shock breakout. (To be launched in 2012.)

Many ground-based telescopes are participating GRB follow-up observations (VLT, Keck, etc.)
FUTURE WORKS

- Looking for more GRB-SN pairs
- Nature of the GRB-SN connection
- Nature of faint GRBs/XRFs
- GRB progenitors
- GRBs and cosmology

GRBs is a very EXCITING field!