Observations of the SN-GRB Connection

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Fellow Stellar Death Detectives

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Outline: SN-GRB Connection

1) Introduction: SN-GRB Connection
   Key Questions: [Q1] Production conditions for SN-GRB? SN Ic with and without GRBs
                   [Q2] Range of jet strengths?

2) For [Q1]
   - Geometry of SN-GRB vs. of SN
   - Environments of SN-GRB vs. of SN

3) For [Q2]
   SN 2008D/XRT080109: jet or no jet?

4) Conclusions & Future Prospects
SN Classification

- Spectra:

  - Thermonuclear SN
  - Core-Collapse SN
  - SN Ia
  - SN II
  - SN Ib
  - SN Ic

  **Broad** lines
  - large expansion \( v \)
  - large KE (10^{52} \text{ erg}) “Hypernova”

  **Stripped-Envelope SN**
SN Classification

- Core-Collapse SN
- Thermonuclear SN

Classification:

• Spectra:
  - HeI
  - ThII
  - SiII

Mass Constraints:

- >10 M☉
DEATHS OF MASSIVE STARS

• Progenitor Models of SN Ib and Ic
  1) Single massive (> 30 $M_\odot$) Wolf-Rayet (WR) stars

  (e.g., Maeder & Conti 2004; Woosley et al. 1995)

  Mass Loss: during MS & WR stage
  a) metallicity-dependent winds
  (Crowther 2007)
  b) or LBV-type eruptions
  (Smith & Owocki 2006)

  2) He stars (8-20 $M_\odot$) in binaries
  (Podsiadlowski et al. 2004)

• Pre-Explosion Observations of SN Ib/c:
  – Cannot differentiate between 1) and 2)
  (Gal-Yam et al. 2005, Maund et al. 2005, Crockett et al. 2007)
  – Interacting SN Ib 2006jc: WR-Star w/ outburst 2 yr prior
  (Foley et al. 2007, Pastorello et al. 2007)
DEATHS OF MASSIVE STARS

• **SN Rates:**
  - 1 SN / (100 years) / (MW-galaxy)

• **How common are SN Ib/c? Local rate:**
  - ~15-20% of all SN
  - ~30% of CC-SN
  - Broad-lined SN Ic (\textbf{SN Ic-bl}): ~5-10% of all SN Ib/c

(Cappellaro et al 1999, Guetta & Della Valle 2007, Leaman et al. in prep)
**Gamma-Ray Bursts: Extreme Explosions**

- Historically 2 “Types”:
  1) Short-hard GRBs
  2) Long-soft GRBs (LGRB):
    - Non-thermal spectra & dramatic variability: \( \delta t/t << 1 \)
    - Relativistic outflow: \( \gamma \sim 1-1000 \)
    - Highly collimated jets: \( \theta \sim 5-10^\circ \)
Gamma-Ray Bursts: Extreme Explosions

Emission from Long GRB:

Meszaros (2001)
SN-LGRB Connection

Spectroscopic ID: broad-lined (bl) SN Ic

1) GRB980425/SN98bw
   \( z=0.0085, \ D=58 \, \text{Mpc} \)  (Galama et al. 1998)

2) GRB030329/SN03dh
   \( z=0.1685 \)
   (Stanek et al. 2003, Hjorth et al. 2003)

3) GRB031201/SN03lw
   \( z=0.1005 \)  (Malesani et al. 2004)

4) XRF020903
   \( z=0.25 \)  (Soderberg et al. 2005, Bersier et al. 2006)

5) GRB060218/SN06aj
   \( z = 0.0335, \ D=160 \, \text{Mpc} \)
   (e.g., Campana et al, Mirabal et al., Modjaz et al. 2006)

Stanek et al. (2003), Matheson et al. (2003)
[see also Review: Woosley & Bloom (2006)]

Nearby GRB (with SN): low-luminosity, less beamed (\( \theta \sim 30^\circ-70^\circ \)), more common (\( \sim 10-10^3 \)x) than cosmological GRBs
(Cobb et al., Soderberg et al., Guetta & Della Valle 2006, etc)
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**Collapsar Model**


- Core Collapse SN Ib/c: **No Hydrogen**
- Stellar Material forms accretion disk around rapidly rotating BH
- Relativistic Jet leaves star
  (Zhang et al. 2004)

- Currently - also other models:
  birth of magnetar
  (Bucciantini et al. 2008, etc)

MacFadyen, Woosley & Heger (2001)
Outstanding Questions

Do all SN Ib/c have jets?

- Many (~20/25) broad-lined SN Ic have NO observed GRB

  viewing angle effects?

  - Probably NO: <10% of all SNIb/c are off-axis energetic GRBs
    (Soderberg et al. 2006)

  - So far, no SN Ib with observed GRB
Outstanding Questions

- Do all SN Ib/c have jets?
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  - Probably NO: <10% of all SN Ib/c are off-axis energetic GRBs
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-[Q1] Which conditions produce jet in GRBs (vs. SN)?
-[Q2] Range of jet strengths?
Late-time Spectroscopy

- Probe deeper into SN ejecta than early-time spectra

- Line shape: geometry of explosion


Asphericities are common in SN Ib/c

- Oxygen ring ejection in SNR E0102.2-7219 (Tuohy & Dopita 1983, Blair et al. 2000)

Gerardy et al. (2002)

Modjaz, Kirshner, & Challis (2008b)
Asphericities are common in SN Ib/c

Modjaz, Kirshner, & Challis (2008b)

Maeda et al. (2008)
SN-GRB distinction: Environs


- high-$z$ GRB ($0.2 < z < 1.0$)

- “GRBs are concentrated on the brightest regions of their hosts.”

![Diagram showing SN II (Non-SN Ia) and LGRB distribution]
Environmental Clues

Local SN Ic and GRB have similar locations compared to host galaxy light

- Similar (large) progenitor masses
- Additional ingredient needed for GRB production


Kelly, Kirshner, & Pahre (2008)
GRB Host Galaxies

- Fruchter et al. (2006):
  - GRB hosts are less luminous & smaller than SN II hosts

![Graph showing luminosity vs. radius with LGRB and SN II (Non-SN Ia) data points.](image)
Host galaxies of LGRBs

Low-metallicity, subluminous host galaxies:

- @ low-z

- Possibly @ high-z
  (Le Floc’h et al. 2003, Fruchter et al. 2006)

Low-metallicity effect: also in GRB radial positions?
(Ramirez-Ruiz et al. 2002)
**Host galaxies of LGRBs**

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Stanek, .., Modjaz et al (2007)

Nearby GRB hosts not unbiased tracers of star formation
Stellar Evolution @ low Z

• Progenitor Stars of GRB:
  – Rotating massive stars @ low Z with Taylor-Spruit Dynamo
  – **High** Angular momentum in core
  – **Removal of H:**
    • Mixing of H (Hirschi et al. 2005)
    • Binary interaction
  – **Massive** core
    (MacFadyen & Woosley 1999; Yoon & Langer 2005; Heger & Woosley 2006)

Ingredients for SN-GRB

• Prediction: SN without GRB have higher Z
Metallicities of Broad-lined SN Ic

- Sample: 12 broad-lined SN Ic w/o GRBs (low $z < 0.15$)
- Data: Own & SDSS
- Gas-Phase Oxygen Abundance estimates from strong line diagnostics (Kewley & Dopita 02 & others)
- Stellar Light Removal
- Central & SN-position measurements b/c of metallicity gradients
- Uncertainty budget

Modyjaz et al. (2008a)
Local SDSS galaxies (Tremonti et al 2004) in KD02 scale

Z-Offset not due to selection effects

Importance of galaxy-impartial SN surveys, e.g., PanSTARRS, LSST!

Modjaz et al (2008a)
**Z-Offset independent of Z-Diagnostic**

KS-Test: 3% 4% 3%

(Pettini & Pagel)

(Te)

(McGaugh 91)

(Kewley & Dopita 02)

“cut-off metallicity”: 0.2- 0.6 Z☉

For most favored scale:

~0.3 Z☉
SN 2008D/XRT 080109: X-RAYS

Swift: satellite: Xrays

Xray Light curve

Discovered by Berger & Soderberg (GCN, Jan 10, 2008)


NGC 2770, D=31 Mpc
WWW Supernova Follow-up

Telescopes used in Modjaz et al.

- APO 2.5m
- CFHT
- Swift
- MDM 2.4m
- FLWO 1.2m, 1.5m, and 1.3m
- Keck
- Gemini South
- CTIO 4m
- VLT
- Magellan
- HET
- MMT
- Lick 3m
- Dupont 2.5m
- TNG
- NOT

Credit: S. Blondin
SN 2008D: Lucky Capture

3 hours before Xrays

Two Infrared Supernovae in NGC 2770: SN 2007uy & SN 2008D/XRT080109

Credit: J. S. Bloom, M. Modjaz (UC Berkeley) and the PAIRITEL SN/GRB Team
SN 2008D: SN Ib (No H, but He)

2 peaks
1st: cooling stellar envelope
2nd: Decay of $^{56}$Ni

Modjaz et al (2008c, submitted)
Did SN2008D/XRT have a Jet?

Emission from GRB:

Meszaros (2001)

- Observable signatures for jet:
  - Gamma-rays: None detected but sensitivity? (Soderberg et al 2008) (Modjaz et al 2008c)
  - X-rays: Debate (see next slide)
  - Optical: No jet (Soderberg et al 2008, Chevalier & Fransson 2008)
  - Radio: No jet (Soderberg et al 2008)
**Xrays from SN 2008D/ XRT 080109**

- **Jet:**
  - Weak or very mildly relativistic - continuum
    (Xi et al. 2008, Li 2008)
  - Stifled Jet
    (Mazzali et al. 2008)

- **No Jet:**
  - X-rays due to shock breakout from compact progenitor plus wind
    (Soderberg et al. 2008, Chevalier & Fransson 2008)
  - XRT 080109 appears different from X-ray Flashes (=weaker cousins of GRBs)
    (Modjaz et al. 2008c)

Soderberg et al. (2008)

\[ L_{x, iso} = 1 \times 10^{43} \text{ erg s}^{-1} \ll L_x(\text{GRB}) \]

\[ E_{x, iso} = 7 (+/- 4) \times 10^{45} \text{ erg} \]

Modjaz et al. (2008c)
Local abundances of SN with and without GRBs

(Kewley & Dopita 02) (McGaugh 91) (Pettini & Pagel, T_e)

"cut-off metallicity": \(~0.3 \, Z_\odot\)

Modjaz et al (2008a)

Z @ site of SN 2008D consistent with those of SN without GRBs
Conclusions

SN-GRB Connection:

- Association between core-collapse SN (broad-lined SN Ic w/o H and He) and LGRBs well-established
- BUT: Why do some SN have GRBs and some don’t?

• Asphericity in even normal SN IIb/Ib/Ic & not only in SN-GRB

• Sites of broad-lined SN Ic (without GRB): higher oxygen abundance than those of SN-GRB: low $Z (<0.3 Z_\odot)$ key-factor for nearby SN-GRB

• SN 2008D: Discovery of 1st SN Ib by Xrays: Jet or No Jet?
  - so far: most probably NO Jet, but stay tuned!

FUTURE: - Do GRBs trace star formation at high $z$?
  - Understanding 2008D & shock breakout
  - More SN coming from big surveys (PanSTARRS, LSST, PTF)