Shedding Light on Short Gamma-ray Burst Progenitors

Joshua Bloom
UC Berkeley
Outline

är Diversity of Gamma-Ray Burst Progenitors
- Review long duration GRBs
- collapsars

- GRB 050509b: short-hard GRB
  - NS-NS/NS-BH merger connection
  - unique host clues
  - internal-external shock consistency

- Raining, pouring: another short burst
γ-ray color ("hardness ratio")

Burst Duration (sec)

long-soft 85%

short-hard 15%

XRF X-ray Rich long-soft

GRB 041219a

GRB 050509b

γ-ray color ("hardness ratio")
GRB Observational Zoo: reflects diverse progenitor population?
c. 2002
The Central Engine: Spinning black hole

Torus feeds central engine: dynamical time of torus determines variability lifetime of mass injection determines duration

Mass-energy conversion from hot neutrinos ($\nu + \bar{\nu} \rightarrow \gamma \gamma$) or Blandford-Znajek process
Paradigmatic Model

- Rotating massive star core collapses to BH forms accretion disk drives collimated outflow

\[
\text{Energy } E_y \approx 10^{51} \text{ erg} \\
\Gamma \approx 100-1000 \\
\text{Duration } \Delta t \approx \text{seconds}
\]

\[
\text{Energy } E_k \approx 10^{51} \text{ erg} \\
\Gamma \approx 10 \rightarrow 1 \\
\Delta t \approx \text{sec - weeks}
\]
Proposed Progenitors

All Satisfy Gross Observational Constraints:

☞ Energetics
☞ Timescale
☞ Occurrence Rate
Progenitors Betray Their Identities Globally and Locally

Redshift Distribution
Location wrt galaxies/star formation
transient emission details
TABLE III

<table>
<thead>
<tr>
<th>Type of Supernova</th>
<th>Type of Galaxy</th>
<th>Spiral Early</th>
<th>Spiral Late</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Elliptical</td>
<td>6 (4)</td>
<td>7 (3)</td>
</tr>
<tr>
<td>II</td>
<td>Elliptical</td>
<td>2 (0)</td>
<td>17 (9)</td>
</tr>
</tbody>
</table>

This classification, although inexact for some supernovae, indicates that in late-type spirals supernovae classed as type II are more frequent than those classed as type I, and suggests that the opposite may be true for early spirals and ellipticals.* In 1938, Baade\textsuperscript{\textasteriskcentered} called attention “... to the curious fact that most of the known supernovae have appeared in the late-type spirals ... quite in contrast to what we find for [the relative frequency of late-type spirals over] the sky at large.” This statement is

* In conversation, October 1951, Minkowski stated that his unpublished investigations lead to a similar conclusion.

ASSOCIATION OF SUPERNOVAE WITH RECENT STAR FORMATION REGIONS IN LATE TYPE GALAXIES

Schuyler D. Van Dyk$^{1,2}$

Naval Research Laboratory, Center for Advanced Space Sensing, Code 4215, Washington, DC 20375-5000

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ABSTRACT

A statistical study has been carried out to constrain the various models for the progenitors of supernovae of types Ia, Ib/c, and II. Star formation regions in late type galaxies are traced out by H \textsc{ii} regions, imaged through photographic and CCD observations, and possible supernova association with these regions is based on the ratio of the angular separation of each supernova from its nearest H \textsc{ii} region to the angular extent of the H \textsc{ii} region in the direction of the supernova. The specific problems of supernova classification and positional uncertainties, as well as the probability of chance superposition, are also considered. The results suggest that type Ia supernovae do not arise from massive, short-lived stellar populations. Type Ib/c and type II supernovae, however, are very likely to be associated with H \textsc{ii} regions and therefore with massive stellar progenitors. The single Wolf–Rayet star progenitor model for the type Ib/c supernovae is not supported. It is not clear from the results whether a difference between the association of type Ib/c supernovae and the association of type II supernovae with H \textsc{ii} regions exists, but this probably results from the effects of small-number statistics for the type Ib/c supernovae. Not all type Ib/c and type II supernovae were found to be associated with detected H \textsc{ii} regions; these supernovae either may have had runaway O star progenitors or were associated with H \textsc{ii} regions below detectability.
Collapsars

Model from Woosley 1993 ("failed Type Ib" SN)

Basic Picture:

25-35 $M_{\text{sol}}$ ZAMS
H (He?) layers lost in wind $\rightarrow$ removal of baryons
Fe core collapses $\rightarrow$ black hole (BH) remnant 2-3 $M_{\text{sol}}$
BH fed by infall $\rightarrow$ torus lifetime sets burst duration
Energy deposition, jet launched, star disrupts
Relativistic outflow at breakout $\rightarrow$ GRB
Explosive nucleosynthesis $\rightarrow$ Ib/Ic SN

Also important:

Role of angular momentum for jet efficiency (e.g., MacFadyen & Woosley 99)
Binarity of Collapsar progenitors
Origin of $^{56}\text{Ni}$ Production
Alternative scenarios: magnetars (e.g., Thompson+ 04)

See Fryer+ 99
Merging Neutron Stars/Black Holes

Initial Conditions:
\[ M_{\text{BH}} > M_p > M_{\text{SN}} \]
\[ M_{\text{BH}} > M_S > M_{\text{SN}} \]
Orbital Separation \( \leq 1 \text{ AU} \)

Primary Evolves off Main Sequence
Primary Expands

- Roche Lobe Overflow
- Mass Transfer
- Primary Collapses

Supernova

Secondary Evolves Off Main Sequence
X-ray Binary Phase

Common Envelope Phase
Orbital Separation Shrinks

Envelope Ejected
Supernova

DNS Binary Merges

from Fryer+ 99
also Eichler 89,
Paczyński 92,
Naryan+ 92...
Last few milliseconds before NS-NS merger

Binary loses angular momentum due to gravitational wave emission

Rapid inspiral after ~100 Myr - few Gyr

1000 revolutions per second

Newly formed Black hole is fed by transient torus, burst duration set by viscous timescale of disk (~few x 10 ms).

Energy deposition $\nu^\nu + B-Z$

Newtonian $\rightarrow$ 3D GR:

Lee+ 05, Ruffert+ 96, Rosswog+ 02, Janka+, ...
NS-NS/BH-NS: Prediction for Early Transient Emission

“mini” supernova
thermal fireball, powered by radioactive/relativistic ejecta

\[ \Delta t \approx 2.2 \text{ day} \left( \frac{M}{0.01 M_\odot} \right)^{1/2} \left( \frac{3V}{c} \right)^{-1/2} \]

\[ L_{\text{max}} \approx 10^{44} \text{ erg/s} \left( \frac{f}{0.001} \right) \left( \frac{M}{0.01 M_\odot} \right)^{1/2} \left( \frac{3V}{c} \right)^{1/2} \]

Li & Paczyński 1998
Pop Synthesis Predictions for Merger Environments

Post 2nd SN:
$10^{-3} \times \text{SNe} \rightarrow \text{NS-NS}$
surviving binaries are tight

Median merger age $10^{8-9}$ yr
some escape host galaxy
median distance $\sim 35$ kpc

Bloom, Sigurdsson, & Pols 99
Pop Synthesis Predictions for Merger Environments

Associated w/ old stars: range of host Hubble-types

Redshift Distribution Biased to lower $z$

Occur at large ($>\text{kpc}$) from birthsites depends $M_{\text{halo}}, r_{\text{disk}}$

Guetta & Piran 05; Fryer+ 99
Redshift Distribution of Long-Duration GRBs

GRB rate consistent with instantaneous star-formation rate

Consistent with production from massive stars

median $z = 1.2$
Long-Soft GRBs: Physically Associated w/ Blue Light

First 20 (2001):
- ✷ follows light of putative host
- ✷ all < 10 kpc (projected) from galaxy

Now:
- ✷ 40+ all associated with late-type galaxies
Smoking Gun: SN-like Light following some GRBs

Direct association with core-collapsed Ic supernovae

980425 and SN1998bw  
Galama+ 98
but low-luminosity GRB

980326, 970228, 011121, ...  
but no spectroscopy
Bloom+ 98, Reichart 99, Garnavich+ 02, ... 

030329 and 2003dh (z=0.17):  
clear indication of contemporaneous SN & GRB  
Stanek+ 03, Chornock+ 03, Eracleous+ 03, Kawabata+ 03
Only Short-Hard GRB Limits

4 small IPN error boxes:
GRB 000607, GRB 001025B, GRB 001204, and GRB 010119

optical/radio afterglows could not be brighter than long duration GRBs
Modern Non-Detections: Instrumental

3 short bursts out of > 100+ post BATSE

Why?

- Requires rapid reads
- Fewer photons
- Fewer low-E photons
- high-E photons penetrating masks?
A Monster Short-Hard Burst...sort of.

Brightest extra-solar transient event ever recorded: $10^{46}$ erg $= 100$ x previous record

SGR 1806–20 ($B \sim 10^{15}$ G) magnetar

Such an event would have resembled a short, hard Gamma Ray Burst (GRB) if it had occurred within 40 Mpc, suggesting that extragalactic SGR flares may indeed form a subclass of GRBs.

Palmer+ 05; also Hurley+ 05

But...SGRs cannot be most BATSE short-hard bursts

Nakar+ 05
GRB 050509b: First Real-Time localization of a Short-hard burst

~40 ms in duration

consistent with high $E_{\text{peak}}$

rapidly fading X-ray afterglow detected in first 300 seconds

Gehrels et al. 05
Swift/BAT+XRT source within ~0.5 Mpc of galaxy cluster center at $z = 0.22$

None of 50+ long GRBs known in clusters

$kT = 5.25^{+3.36}_{-1.68}$ keV

D. Pooley
050509b Observations

Keck/LRIS

Chance coincidence with this elliptical galaxy small (< 1%)

Bloom+ 05
Elliptical Host: no evidence for recent star formation

$z=0.225$
No detectable optical transient from 30 sec to 8 days

10+ mags fainter compared to long-soft GRBs at similar epochs

$10^3$ times deeper than nominal Paczynski & Li “mini” supernova
low radioactive coupling

Still...consistent with being a faint analogue of long GRB afterglows
Later-time upper limits constrain all types of SNe-like emission

$M_B > -13.3 \ @ \ z=0.225$

$\approx 1 \ \text{mag fainter than faintest SN known}$

Hjorth+ 05
050509b: Internal/External Shock Consistency

$L_X \propto E_{\gamma,\text{iso}}$

$L_X$ proxy for KE of blastwave

$E_{\gamma,\text{iso}}$ energy released from IS

Low-energy analogue of long duration GRBs
<table>
<thead>
<tr>
<th>Origin of the Species</th>
<th>Leading Theories for GRBs</th>
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</thead>
<tbody>
<tr>
<td><strong>Collapsar</strong></td>
<td>massive star explodes to make GRB + supernova e.g., GRB 030329</td>
</tr>
<tr>
<td></td>
<td>from young stars (&lt; few million years old)</td>
</tr>
<tr>
<td></td>
<td>near star formation</td>
</tr>
<tr>
<td></td>
<td>~10 seconds</td>
</tr>
<tr>
<td><strong>Magnetar</strong></td>
<td>star quake from highly-magnetized neutron star e.g., SGR 1806-20/GRB 041227</td>
</tr>
<tr>
<td></td>
<td>from young stars (&lt; tens of millions years old)</td>
</tr>
<tr>
<td></td>
<td>near star formation</td>
</tr>
<tr>
<td></td>
<td>&lt; 1 second</td>
</tr>
<tr>
<td><strong>Mergers</strong></td>
<td>old compact objects (black holes and neutron stars) coalesce after binary orbit decays</td>
</tr>
<tr>
<td></td>
<td>from old stars (&gt; tens of millions years; ~Gyr)</td>
</tr>
<tr>
<td></td>
<td>not closely associated with star formation</td>
</tr>
<tr>
<td></td>
<td>&lt; 1 second</td>
</tr>
</tbody>
</table>
Predictions and Outcroppings of Merger Scenario

- Not all short-hard GRBs should be near ellipticals, but rates should correlate with old stars: variety of Hubble-type hosts
- Observational bias towards gas-rich environments: enhancement in afterglow luminosity favors detection in cluster environments?

\[ \text{few} \times 10^8 \text{ yr (median) delay from star burst...} \]

\[ \rightarrow \text{lower redshift distribution (factor of } \sim \text{few enhancement at } z=0) \]

\[ \rightarrow \text{improves chances for GW detection} \]

see also Fryer, Woosley, & Hartmann 99, Bloom, Sigurdsson, & Pols 99
GRB 050709: HETE-2 short burst just localized to a galaxy @ z=0.16

Evidence for recent star formation in the spectrum reflecting host diversity

Price+ 05
Summary

GRB 050509b
- discovery of the cosmological distance scale
- remarkable concordance with merger models
- diversity of progenitors

Short-Hard GRBs
- low radioactive heating from relativistic ejecta
- emission mechanism for prompt and afterglow
  consistent with long-duration GRBs

Establishing a Connection of GRBs to GW astronomy