GRB Observations and Follow-up by Swift

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NASA-GSFC

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Fermi Summer School
Lenape or Delaware Indians

- 1632 – Zwaanendael
- 1664 – Hoernkills
- 1673 – New Deale
- 1831 – Lewes
Outline

→ Gamma ray burst background
→ The Swift mission
→ Swift GRB results
→ Swift follow-up of Fermi GRBs
Two types:
- Short GRBs ($t < 2s$)
- Long GRBs ($t > 2s$)

Origin:
- NS-NS mergers: SGRBs
- Massive star collapse: LGRBs

Redshift range:
- SGRBs: $0.2 - \sim 2$
- LGRBs: $0.009 - 8.2$

Energy release in $\gamma$-rays:
- SGRBs: $10^{49} - 10^{50}$ ergs
- LGRBs: $10^{50} - 10^{51}$ ergs

Jet opening angle:
- SGRBs: ? (5-20) deg
- LGRBs: \sim 5 deg

Both types have delayed & extended high-E emission
GRB Spectra

Prompt

100 keV

Guiriec+ 12

Afterglow

Butler+ 06

GRB 051111

Optical/IR/UV
Radio
XRT

Frequency [Hz]
VELA Discovers GRBs

Klebesadel, Strong & Olson 1973

Ray Klebesadel 2009
Compton Observatory Era

Sky Distribution of BATSE GRBs
The Fireball!

X-ray afterglow GRB 970228

BeppoSAX satellite

GRB Fireball Model

Mészáros & Rees 1997
Developments ~2000

Scientific urgency for new GRB mission

Recognized:
* GRBs are new tools for
  - high-z universe
  - SN physics
  - jet physics

However:
* Long GRBs poorly understood
* Short GRBs not understood

Needed:
* Rapid response & multi-wavelength observatory

New CdZnTe detectors enable advanced $\gamma$-ray camera

medical imaging brain scan
The Swift Mission
Swift Mission

3 instruments, each with:
- lightcurves
- images
- spectra

Rapid slewing spacecraft

BAT Position - 2 arcmin

XRT Position - 5 arcsec

UVOT Position - < 1 arcsec

BAT Position - 2 arcmin

XRT Position - 5 arcsec

UVOT Position - < 1 arcsec

T<10 sec

T<90 sec

T<2 min
Observatory Properties

**Orbit**
600 km x 28° inclination

**BAT**
New CdZnTe detector
2 sr FoV
13 – 150 keV

**XRT**
Arcsec GRB positions
24' x 24' FoV
0.2- 10 keV
CCD spectroscopy

**UVOT**
Sub-arcsec positions
17' x 17' FoV
170 – 650 nm
filters = grism

**Spacecraft**
Autonomous slews 20-75s
BAT CdZnTe Detectors

32,000 CZT detectors

13 – 300 keV
Florida 2004 - Hurricane Alley

Hurricanes:
- Charley Aug 13
- Frances Sept 4
- Ivan Sept 10
- Jeanne Sept 25

Jeanne
Vehicle Assembly Building damage
Let's Launch Anyway !!!
XRT & UVOT Galaxy Mugshots

M100

M101

Stefan’s Quintet

NGC 7469

V,B,U

W1,M2,W2

X-ray

M83

NGC 6946

M51

UGC 272

V,B,U

W1,M2,W2

X-ray
773 GRBs as of yesterday
85% with X-ray detections
60% with optical detection
250 with redshift (41 prior to Swift)
72 short GRBs localized (0 prior to Swift)

Swift Statistics
Swift Data
GRB 130524A

BAT lightcurves

XRT lightcurve

UVOT image
Long GRBs
# High Redshift GRBs

<table>
<thead>
<tr>
<th>z</th>
<th>Look-Back Time (Gyr)</th>
<th>GRB</th>
<th>Optical Brightness</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.4</td>
<td>13.1</td>
<td>090429B</td>
<td>K = 19</td>
</tr>
<tr>
<td>8.2</td>
<td>13.0</td>
<td>090423</td>
<td>K = 20</td>
</tr>
<tr>
<td>~8</td>
<td>13.0</td>
<td>120923A</td>
<td></td>
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<tr>
<td>7.5</td>
<td>13.0</td>
<td>100905A</td>
<td>H ~ 19</td>
</tr>
<tr>
<td>6.7</td>
<td>12.8</td>
<td>080813</td>
<td>K = 19</td>
</tr>
<tr>
<td>6.3</td>
<td>12.8</td>
<td>050904</td>
<td>J = 18</td>
</tr>
<tr>
<td>6.2</td>
<td>12.8</td>
<td>120521C</td>
<td></td>
</tr>
<tr>
<td>5.6</td>
<td>12.6</td>
<td>060927</td>
<td>I = 16</td>
</tr>
<tr>
<td>5.3</td>
<td>12.6</td>
<td>050814</td>
<td>K = 18</td>
</tr>
<tr>
<td>5.11</td>
<td>12.5</td>
<td>060522</td>
<td>R = 21</td>
</tr>
</tbody>
</table>

**GRBs:** brightest high-z sources

**XRT Lightcurve**

**HST image**
GRB Host Spectroscopy

GRB 050505  z=4.2  12.2 Gyr

Keck/LRIS  2005 May 6.26

$z_1 = 4.2748$
$z_2 = 2.2650$
$z_3 = 1.6948$

Berger+06

Metallicity

Star Formation Rate

Savaglio 06

Robertson & Ellis 11

Kistler+ 09

GRBs

Metallicity vs. Redshift

$Z/Z_\odot$

$Hubble$ time (Gyr)

Star Formation Rate vs. $t$ [Gyr]

$\rho_\star [M_\odot yr^{-1} Mpc^{-3}]$

$z$
Star Formation Rate

rate to balance H I formation Madau+ 99
### History of the Universe

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>17 Myr</td>
</tr>
<tr>
<td>10</td>
<td>480 Myr</td>
</tr>
<tr>
<td>5</td>
<td>1.2 Gyr</td>
</tr>
<tr>
<td>0.5</td>
<td>8.7 Gyr</td>
</tr>
<tr>
<td>0</td>
<td>13.7 Gyr</td>
</tr>
</tbody>
</table>

**GRB 090429B** 9.4

- **Big Bang - Hot ionized gas**
- **The Universe becomes neutral and opaque**
- **Stars and galaxies form**
- **Reionization starts**
- **Cosmic Renaissance**
- **Dark Ages end**
- **Reionization complete**
- **Galaxies evolve**
- **Solar System forms**

Djorgovski et al.
GRB 060218: GRB + Supernova

Super-long GRB - ~35 minutes
BAT, XRT, UVOT during GRB
z = 0.033  d = 145 Mpc
SN 2006aj  SN Ib/c
E_{iso} = few x 10^{49} erg  - underluminous

Campana+ 006

SN 2006aj
3 GRB SNe

SNe Ic

Pian+ 06

Campana+ Mazzali+, Pian+, Soderberg+ 06
Long GRB Scenario

Massive star with H & He envelope stripped

Rapidly rotating
Long GRB Scenario

- Massive star
- Rapid rotation
- Proto-NS
- Neutrino emission
- Collapse $\tau < 1$ sec

Diagram:

- Massive star
- Rapid rotation
- Proto-NS
- Neutrino emission
- Collapse $\tau < 1$ sec
Collapsar Model

Collapse to BH

BH
Long GRB Scenario

Accretion onto BH
\( \tau \sim 10\text{'}s \text{ sec} \)

Jet emergence
\( \tau \sim 10 \text{ sec} \)

MacFadyen & Woosley
Short GRBs
Short Burst Variety

GRB 060313

GRB 130515
Cracking the Short Burst Problem

BAT - 30 ms duration

XRT - faint source, fading

Host - cD elliptical (L = 3 L*)
- low star formation rate
- \( z = 0.225 \) (817 M yrs)

No supernova to deep limits

GRB 050509B

VLT image

Hjorth+ 05

Gehrels+ 05; Bloom+ 06
Short vs Long GRBs

In non-SF and SF galaxies
No SNe detected
Possible merger model

In SF galaxies
Accompanied by SNe
Collapsar model well supported
Short Burst HST Images

Fong, Berger & Fox 10
Short GRBs Merger Model

Credit: Daniel Price and Stephan Rosswog
Short GRB Info

Swift localized 72 short GRBs

Weak afterglow

Low average redshift

Jet opening angle

\[ \theta_{\text{jet}} \sim 5 - 20^\circ \] short
\[ \theta_{\text{jet}} \sim 5^\circ \] long

Fong+ 12

Berger+ 09
Why Black Holes?

- **Energetics**
  
  Both BH & NS have enough energy

- **Time variability**
  
  ms variability → 300 km

- **Jets**
  
  May be best BH discriminator

---

**Black Hole Energetics**

\[
\text{Energy} = \frac{G M m}{r} = \frac{1}{2} mc^2 \quad \text{for} \quad r = R_{Sch} = \frac{2 GM}{c^2} = 3 \times 10^{54} \text{ ergs} \quad \text{for} \quad m = 3 M_\odot
\]
Swift Transient - Sw J1644+57

- Highly erratic $\gamma$-ray and X-ray light curve, March 28, 2011
- Like a GRB, but lasting 2 days instead of 20 seconds
- Tidal disruption event beamed at us

Swift Light Curve

HST Image

Center of galaxy at $z=0.35$
Fermi GRB Follow-up
Swift Data & Comm

Mission Operations Center (MOC)

Payload
- BAT
- XRT
- UVOT

Malindi

Spacecraft
- Spectrum Astro
- Rapid Autonomous Slews

TDRSS

GSFC

PSU

Science Center

HEASARC
- UK
- Italian Archives

GCN & Web

User Community
Evolving Observing Time

2005
- 35% Swift GRBs
- 46% TOOs
- 13% GI targets / Fill-ins
- 6% SAA & Calibration

2008
- 17% Swift GRBs
- 27% TOOs
- 38% GI targets / Fill-ins
- 18% SAA & Calibration

2012
- 18% Swift GRBs
- 30% TOOs
- 35% GI targets / Fill-ins
- 17% SAA & Calibration

TOOs per Year

- 2004: 100
- 2005: 100
- 2006: 200
- 2007: 400
- 2008: 600
- 2009: 800
- 2010: 1000
- 2011: 1200
- 2012: 1400

Legend:
- Swift GRBs
- Target of Opportunities (TOOs)
- GI targets / Fill-ins
- SAA & Calibration
# Swift Follow-up of LAT GRBs

<table>
<thead>
<tr>
<th>GRB</th>
<th>Duration</th>
<th>Redshift</th>
<th>Event Description</th>
<th>Follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 080825C</td>
<td>22 s</td>
<td></td>
<td>extended emission</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 080916C</td>
<td>66 s</td>
<td>z = 4.35</td>
<td>extended emission</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 081024B</td>
<td>0.8 s</td>
<td></td>
<td>extended emission</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 081215A</td>
<td>7.7 s</td>
<td></td>
<td>extended emission</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 090217</td>
<td>33 s</td>
<td></td>
<td></td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 090228</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRB 090323</td>
<td>150 s</td>
<td>z = 3.57</td>
<td>AG dominant, ext emm</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 090328</td>
<td>100 s</td>
<td>z = 0.736</td>
<td>AG dominant, ext emm</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 090510</td>
<td>2.1 s</td>
<td>z = 0.903</td>
<td>extended emission</td>
<td>BAT/XRT</td>
</tr>
<tr>
<td>GRB 090626</td>
<td>70 s</td>
<td></td>
<td>extended emission</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 090902B</td>
<td>21 s</td>
<td>z = 1.822</td>
<td>34 GeV photon</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 090926A</td>
<td>20 s</td>
<td>z = 2.1062</td>
<td>extended emission</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 091003</td>
<td>21 s</td>
<td></td>
<td>extended emission</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 091031</td>
<td>35 s</td>
<td></td>
<td></td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 100116A</td>
<td>110 s</td>
<td></td>
<td></td>
<td>sun cnstrmt</td>
</tr>
<tr>
<td>GRB 100225A</td>
<td>13 s</td>
<td></td>
<td></td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 100414A</td>
<td>26 s</td>
<td>z = 1.468</td>
<td></td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 100708A</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>GRB 100728A</td>
<td>198 s (BAT)</td>
<td>z = 1.567</td>
<td>during late flares (found 10-10)</td>
<td>BAT/XRT</td>
</tr>
<tr>
<td>GRB 100826A</td>
<td>150 s (Konus)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRB 110120A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRB 110328B</td>
<td>~40 s</td>
<td></td>
<td>soft LLE only, large error circle</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 110428A</td>
<td>~200 s</td>
<td></td>
<td>high energy emission</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 110625A</td>
<td>~30 s</td>
<td></td>
<td></td>
<td>BAT/XRT</td>
</tr>
<tr>
<td>GRB 110721A</td>
<td>24 s</td>
<td>z = 0.382</td>
<td>&gt;20 MeV only</td>
<td>BAT/XRT</td>
</tr>
<tr>
<td>GRB 120226A</td>
<td>57 s</td>
<td></td>
<td>ground analysis</td>
<td>BAT/XRT</td>
</tr>
<tr>
<td>GRB 120328B</td>
<td>31 s</td>
<td></td>
<td></td>
<td>BAT/XRT</td>
</tr>
<tr>
<td>GRB 120624B</td>
<td>271 s</td>
<td></td>
<td>bright GBM, ground optical</td>
<td>BAT/XRT</td>
</tr>
<tr>
<td>GRB 120709A</td>
<td>30 s</td>
<td></td>
<td></td>
<td>XRT</td>
</tr>
<tr>
<td>GRB 120711A</td>
<td>135 s</td>
<td>z = 1.405</td>
<td>INTEGRAL GRB</td>
<td>XRT</td>
</tr>
<tr>
<td>GRB 120830A</td>
<td>1.3 s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRB 120911B</td>
<td>30 s</td>
<td></td>
<td>IPN burst</td>
<td>sun constraint</td>
</tr>
<tr>
<td>GRB 120916A</td>
<td>53 s</td>
<td></td>
<td>IPN burs</td>
<td></td>
</tr>
<tr>
<td>GRB 121011A</td>
<td>66 s</td>
<td>LLE</td>
<td></td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 130305A</td>
<td>29 s</td>
<td></td>
<td></td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 130310A</td>
<td>2.4 s</td>
<td></td>
<td>ARR, very hard BATSE</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 130325A</td>
<td>8 s (Konus)</td>
<td></td>
<td>not in prompt, only in afterglow</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 130327B</td>
<td>62 s</td>
<td></td>
<td>with AGILE</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 130427A</td>
<td>162 s (BAT)</td>
<td>z = 0.340</td>
<td>with Swift, brightest burst to date</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 130502B</td>
<td>24 s</td>
<td></td>
<td>called in FOT for Swift TOO</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 130504C</td>
<td>74 s</td>
<td></td>
<td>XRT detection at 18 hours</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 130518A</td>
<td>48 s</td>
<td>z = 2.49</td>
<td>BAT untriggered at edge of FoV</td>
<td>Swift</td>
</tr>
</tbody>
</table>

Note: BAT/XRT indicates follow-up by both BAT and XRT instruments. Swift indicates follow-up by the Swift satellite. Swift FOLLOW-UP indicates specific Swift follow-up details.
Auto Sky Tiling

XRT 7 Tile Pattern

LAT GRB position accuracy <1 deg

GRB GRB position accuracy ~5 deg
Covering Large Error Boxes

- Large error boxes from GBM, IPN, & grav. waves
- Tiling & coordination with wide-field telescopes
- In preparation of ALIGO/Virgo, goal is to detect a GBM afterglow with PTF + Swift
Swift XRT Tiling LAT Error Box

Position (degrees)

Position (degrees)

good LAT positions

7 tile XRT 4 hours
Swift XRT Tiling GBM Error Box

- Best GBM positions
- 37 tile XRT 0.9 day
Summary

GRBs are powerful explosions
- most luminous sources at all wavelengths
- afterglow lasts for days

Long GRBs
- due to core collapse to black hole of massive star
- new probe of high redshift universe
- produce energetic, high-velocity supernovae

Short GRBs
- associated with old stellar populations
- likely caused by NS-NS mergers
- exciting sources for gravitational wave observations

Long & short GRBs are likely signatures of BH birth

Swift & Fermi are working together to learn the nature of GRBs and use them to study the universe