The Swift Gamma-Ray Burst Explorer: Early Views into Black Hole Creation

David Burrows (Penn State) and the Swift team
Setting the Stage: 1967

- Vela satellites launched in mid-1960s to monitor the Atmospheric Test Ban Treaty
- Strange pulses discovered in 1969 by Ray Klebesadel of LANL
  - Data classified until 1973
30 Years Later: 1997

- Compton Gamma-Ray Observatory launched in April 1991
- BATSE: 2609 bursts in 8.5 years
  - Bursts are isotropic
  - Frequency ~ 1 burst per day
  - Not clear whether they are nearby or distant
The celestial sky

GRBs are distributed isotropically on the sky.
**GRB Characteristics (BATSE)**

- Characteristics:
  - About 1 per day
  - Powerful: brightest γ-ray object in sky
    - Typically $10^{51}$ ergs
  - Isotropic distribution
  - Finite Extent
  - Unique lightcurves
  - Bimodel distribution of durations
GRB Models

Hypernova

Young (few million yrs)
In star-forming galaxies
Long Bursts
Hypernova
GRB Models

**Hypernova**
- Young (few million yrs)
- In star-forming galaxies
- Long Bursts

**Merging Neutron Stars**
- Old (few billion yrs)
- Not in star-forming galaxies
- Short Bursts??
2/10/97: Meszaros and Rees GRB relativistic fireball model published in ApJ; predicted broadband afterglows

Emission mechanism: synchrotron emission from power-law distribution of electrons in highly relativistic outflows
Observational Breakthrough: 1997

- Beppo-SAX makes the first X-ray image of a GRB afterglow.
The Beppo-SAX/HETE-II era

- GRB 970228: first detection of X-ray and optical afterglows
- GRB 970508:
  - First redshift of GRB afterglow (Keck)
  - Also first radio detection of afterglow (VLA – scintillation)
    - Scintillation demonstrated that central source was compact => BH
    - Scintillation also proved superluminal expansion => fireball shock model
- GRB 990123: first optical observation of GRB (ROTSE)
  - “Biggest explosion since Big Bang”
- 55 afterglows discovered by Beppo-SAX and HETE-2
  - Typical delay of 6-8 hours in position determination
Swift Instruments

- **Burst Alert Telescope (BAT)**
  - New CdZnTe detectors
  - Detect ~100 GRBs per year depending on logN-logS
  - Most sensitive gamma-ray imager ever

- **X-Ray Telescope (XRT)**
  - Arcsecond GRB positions
  - CCD spectroscopy

- **UV/Optical Telescope (UVOT)**
  - Sub-arcsec imaging
  - Grism spectroscopy
  - 24th mag sensitivity (1000 sec)
  - Finding chart for other observers

- **Spacecraft**
  - Autonomous re-pointing, 20 - 75 sec
  - Onboard and ground triggers
Burst Alert Telescope (BAT)

BAT Characteristics

- E Range: 15 - 150 keV (12-300)
- E Resoln: 7 kev (5)
- Loc Resoln: 1-4 arcmin (1-4)
- PSF: 22 arcmin (21.8)
- 2 steradian field of view
- 32K CZT dets, 5200 cm2
- Autonomous operations
Coded-Aperture Imaging

Coded Aperture Mask Pattern

5 mm square Pb tiles

Source Photons “Encoded” by Partially Blocked Aperture
Can be Decoded in Data Analysis to Determine Source Position
Missing Pixels = Graceful Degradation in Sensitivity
The X-Ray Telescope
The UV/Optical Telescope
Observing Scenario

1. Burst Alert Telescope triggers on GRB, calculates position to ~ 1 arcmin
2. Spacecraft autonomously slews to GRB position in 20-70 s
3. X-ray Telescope determines position to ~ 3 arcseconds
4. UV/Optical Telescope images field, transmits finding chart to ground

BAT Burst Image $T\sim 10$ sec
XRT Image $T\sim 100$ sec
UVOT Image $T\sim 300$ sec
The Swift Observatory

- Launched: 20 November 2004
- BAT First Light: 3 December 2004
- XRT First Light: 11 December 2004
- First BAT Burst: 17 December 2004
- First XRT Afterglow: 23 December 2004
- UVOT First Light: 12 January 2005
- Data public since 5 April 2005
Pixel = 17'

FWHM = 22'

Position < 4'
BAT Energy Resolution

On-Orbit Am241 Cal Spectrum
32K detectors summed together

5 keV FWHM at 60 keV
**BAT Bursts**

- 53 GRBs detected/imaged since Dec. 17 (29.5 weeks as of 7/26/05)

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Light Curves of First 25 BAT GRBs

- = prompt slew
- = detected by XRT
- = detected by UVOT
- = detected by ground-based optical/IR
- = redshift measurement
UVOT Detections of BAT GRBs

- Detected 8/38 with UVOT
  - Why so few?? Big mystery!
  - UVOT upper limits are quite faint and very early for many of these
  - However, 21 have ground-based detections (typically R, I, J, or K)
    - High z? (perhaps in some cases)
    - Dust extinction? (some evidence supporting this)
    - Magnetic suppression?
GRB 050318: the first UVOT afterglow

![Image of UVOT afterglow with relevant coordinates and time stamps.

Fig. 1. Stacked UVOT-V filter image of the field with the transient source at RA = 03h 12m 51s.15, Dec = -46° 23' 48".7 (J2000) and a 3'' BAT error circle and 6'' XRT error circle overlaid. Total exposure time for the stacked image is 3,732s.]
GRB 050318: the first UVOT afterglow
GRB 050319: UVOT Lightcurve
**XRT Detections of BAT GRBs**

- Detected 39/40 with XRT (observed @ T < 200 ks)
  - Observed two during burst
  - 27/39 Swift detections were prompt observations (< 300 s)
    - 24/27 have fast decline or flare within first ~5 minutes
  - 11 have redshift measurements:
    - Average redshift: 1.8 (compared with about 1 for Beppo-SAX bursts)
    - Highest redshift: 4.27 (2\textsuperscript{nd} highest on record)

- Detected 1/2 HETE burst with XRT
- Detected 4/7 Integral bursts with XRT
XRT Positional Accuracy

Daniele Malesani – MISTICI collaboration

GRB 041223
VLT
J-band
Dec 24.261

Afterglow

This work

GRB 050306

Daniele Malesani – MISTICI collaboration

GRB 050124
Keck/NIRC
K_s-band
Jan. 25.501 UT

Berger et al. 2005

Average: 2.6"

XRT GRB Position Errors

Berger et al. 2005
XRT Afterglow Summary

Compare GRB050215b with SAX/XTE/XMM/Chandra AG

At least 3 shapes of afterglows. Out of 24 prompt observations, we have:

- Type A (3)
- Type B (10)
- Type C (11)
Type A Afterglows

GRB 050128
GRB 050401
GRB 050525A?
GRB 050128

XRT in Manual State, PC Mode
- **108 s after burst trigger**
- Bright, piled-up X-ray source
- Very shallow decay index in first orbit
\( \alpha_1 = -0.27 \pm 0.10 \)

\( \alpha_2 = -1.30 \pm 0.15 \)

\( t_{\text{break}} = 1470 \text{ s} \)

\[ F_X \propto t^\alpha \]

Jet Break

Relativistic beaming: \( \theta \sim \Gamma^{-1} \)
GRB 050128 spectrum

\[ \Gamma = 1.66 \pm 0.07, \quad N_H = 4.8 \times 10^{20} \text{ (for all three orbits)} \]

\[ F_x = 1.91 \times 10^{-10} \text{ cgs} \]

\[ F_x = 1.61 \times 10^{-11} \text{ cgs} \]

\[ F_x = 5.74 \times 10^{-13} \text{ cgs} \]

GRB 050126

Observed at T+131 s, Manual State / PC mode

- 3.1 arcseconds from Keck counterpart
- UVOT did not observe due to proximity to Vega
**GRB 050126**

GRB050126: BAT and XRT flux light curve in the 0.2–7 keV band

Power Law fitted only on the first XRT segment

\[ \alpha = -2.1 \]

\[ \alpha = -1.2 \]

\[ T_0 = 26 \text{ Jan} 2005 \ 12:00:53 \text{ UT} \]

Tagliaferri et al. 2005, Nature
GRB 050319

Detected at 09:31:18 UT (T+ 87s)

Source is at:
RA(J2000) = 10h 16m 48.1s,
Dec(J2000) = +43d 32' 52.3"

Detected by ROTSE telescope and by UVOT

- 3.1 arcseconds from ROTSE counterpart
- First UVOT prompt lightcurve
GRB 050319: XRT Lightcurve

$\alpha_1 = -2.9 \pm 0.3$

$\alpha_2 = -0.45 \pm 0.03$

$\alpha_3 = -1.09 \pm 0.03$

$t_1 = 266 \pm 18$

$t_2 = 23550 \pm 7150$

Possible models for initial decay

1. $t_0$ offset: expect single power-law, $\beta_1 = \beta_2$
2. Prompt shock stops: expect $\beta_0 = \beta_1$
3. Photospheric emission: expect $\beta_0 < \beta_1$ (steeper)
5. Jet cocoon: thermal emission
6. Multiple collimated mini-jets

Observationally:

$\beta_0 > \beta_1 = \beta_2$ for GRB 050219a

$\beta_1 < \beta_2$ for GRB 050315
Possible models for initial decay

1. $t_0$ offset:
   Q: when does the afterglow begin fading as a power-law?
   a) when burst occurs? Or
   b) when shocks hit external medium?

   Perhaps we are using the wrong $t_0$ and these bursts are really a single power-law decline, beginning when the afterglow (external shock) begins
Compare with GRB011121 light curve

L. Piro et al. 2004, astroph_0412589
t0 error

t0 changed to 240s after trigger

L. Piro et al. 2004, *astroph_0412589*
t0 error

M. Goad
Possible models for initial decay

2. Unified mechanism:
   Q: Are we seeing a single mechanism that is responsible segments 0 and 1?

   The behavior in segment 1 could be a continuation of the end of the prompt emission under several scenarios:
   a) Internal shock ends
   b) Off-axis emission and light delay effects

   In these cases, expect smooth transition from segment 0 to segment 1.

   No relationship between segment 1 and segment 2 (as shown).
Jet Break

Jet

Torus

$\Delta t$
Possible models for initial decay

Possible models for initial decay

3. Unrelated to prompt emission. Possible “exotic” models for segment 1:
   a) Photospheric emission
   b) Jet cocoon: thermal emission
   c) Multiple collimated mini-jets

In these cases, expect no relationship between segment 0 to segment 1.

No relationship between segment 1 and segment 2 (as shown).
Type C Afterglows

050406
050421
050502B
050607
050712
050713A
050714B
050716
050724?
050726
Detected at 15:58:48.4 UT

Displaced observation of South Galactic Pole (BAT calibration target)

Source is at:
RA(J2000) = 02h 17m 52.6s, Dec(J2000) = -50d 11' 18.8"

Detected by Magellan telescope and by UVOT
GRB 050406 XRT Lightcurve

Increases at early times – very puzzling!

GRB 050421

\[ \alpha = -2.8 \]

GRB050421

IrPD sl, IM, puPD, IrPD po, WT, PC

rate (count s^{-1})

\( \alpha = -2.8 \)

5 arcmin
within settled position

time since burst (s)

ratio
Giant X-ray Flare: GRB050502b

GRB Fluence:
8E-7 ergs/cm²

Flare Fluence:
9E-7 ergs/cm²

Giant X-ray Flare: GRB050502b

Flare Mechanism

- Rapid increase and decrease
  - Inconsistent with external shock
- Enormous increase in GRB 050502B
  - Inconsistent with Inverse Compton mechanism
- Same underlying afterglow before and after
  - Inconsistent with additional energy added to external shock

Most likely explanation is that internal shocks continue at much later times than the prompt $\gamma$-ray emission.

Late-time emission occurs at larger radius, resulting in slower rise/fall and softer energies.
Late emission also has higher Lorentz factor because shocks expand in channel evacuated by earlier shocks.
XRT Afterglow Types

At least 3 shapes of afterglows. Out of 24 prompt observations, we have:

- Type A (3)

- Type B (10)

- Type C (11)
**GRB050509b: First Short GRB Afterglow**

\[ t_{90} = 0.04 \text{ s}, \text{Fluence} = 2\times10^{-8} \text{ ergs/cm}^2 \]

XRT counterpart in first 400 s, fades rapidly. 11 photons total.

Location in cluster at \( z=0.226 \), near early-type galaxy.

Possible NS-NS merger?

Gehrels et al. 2005, Nature

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XRT error circle on VLT image. XRT position is 9.8” from a bright elliptical galaxy at \( z=0.226 \)
GRB050509b: UVOT Image

R=B+V
G=U+W1
B=W2+M2

Location in cluster at z=0.226, near early-type galaxy. No UV emission from candidate galaxy

Possible NS-NS merger?
GRB050509b: First Short GRB Afterglow

Location in cluster at $z=0.226$, near early-type galaxy ($z=0.2249$). But what about S1??
- S1 found to not fade
- S1 is extended
- S1 is blue in color
- S1 is presumably a background star-forming galaxy
GRB050709: Second Short GRB Afterglow

- Discovered by the HETE-II satellite
- X-ray counterpart found by Chandra X-ray Observatory
- Optical counterpart found by ground-based telescopes
  - Located at edge of elliptical galaxy at z=0.16

Danish 1.54m La Silla telescope: courtesy Jensen et al. 2005, GCN 3589; Price et al. 2005, GCN 3612)
Summary

- BAT is working flawlessly and producing great data!
- BAT has now observed 53 GRBs (as of 26 July 2005)
  - 5 XRFs
  - 9 FREDs (3 are multiple FREDs)
  - 3 short bursts
  - One extremely dark burst (Rc than 26\textsuperscript{th} mag)
  - Relatively few false triggers
  - Average rate is \(~ 90/\text{year}\)
  - Average on-board positional accuracy for the
    34 with XRT positions: \textbf{55 arcseconds}

- UVOT has now observed 38 afterglows
  - Excellent UV telescope
  - 8 GRB afterglow detections, one redshift measurement
  - Major mystery: why so few UVOT detections?
Summary

• XRT has now observed 40 afterglows
  – 39 detected
  – 24 prompt slews (< 5 minutes after burst)
  – Two prompt emission
  – Three short burst afterglows
  – Average positional accuracy for the
    24 with ground positions: **3.4 arcseconds**
  – > 50% of spectral fits have excess (intrinsic) \( N_H > 10^{21} \)

• XRT is observing afterglows \( 10^2 \) – \( 10^3 \) times fainter than similar observations with Beppo-SAX. New behaviors are appearing at early times.
Summary

• Public data release began April 5, 2005
  – http://swift.gsfc.nasa.gov/docs/swift/sdc/

• As Swift observations become routine, we expect new insights into GRB formation and environments
  – Solution to Short GRB mystery (merging NS?)
  – Systematic investigation of GRB environments (ISM vs wind)
  – Redshifts
  – X-ray spectral lines???
XRT Collaborators

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