The *Swift* Gamma-ray Burst Explorer: Early views into Black-hole Creation

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Overview

- The discovery of Gamma-ray Bursts
- The *Swift* Mission
  - *Swift* afterglows - an early insight
  - Catching the afterglow for the first time
- The detection of the elusive Short Burst
  - The most distant GRB ever detected
- GRB 060218
  - The beginnings of a SN?
The Discovery of Gamma-ray Bursts: 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
~25 Years after discovery: 1991

- Compton Gamma-Ray Observatory launched in April 1991
- BATSE: 2609 bursts in 8.5 years
  - Bursts are isotropic
  - Frequency \( \sim 1 \) 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
  - Bi-model distribution of durations
Theoretical Predictions


\[ F(\nu, t) \propto t^\alpha \nu^\beta \]
Hypernova

- The collapse of the core of a massive star to form a Black-Hole
- ~millions years before the explosion the fuel start to dwindle
- The envelope is lost
- Remaining fuel is depleted losing radiation pressure
- Core collapses and forms a Black-Hole
- After ~few seconds streaming particle jets blast through the outer shells of the star
Binary Merger Theory

- Start with a NS-NS or an NS-BH pair orbiting each other........
- The huge Gravitational force causes them to orbit each other with increasing velocities
- As they get closer together, they begin to become misshapen as they rip each other apart
- They finally merge in an instant, forming a Black-Hole shooting out jets of gamma-rays
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 \( \Rightarrow \) BH
    - Scintillation also proved superluminal expansion \( \Rightarrow \) 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
What Next?

- Need gamma-ray burst detector with large FoV
- Rapid follow-up ~minutes
  - X-ray Afterglow
  - Optical Afterglows
- Need to get localised positions rapidly to the ground
Swift Instruments

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

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

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

- Spacecraft
  - Autonomous re-pointing, 20 - 75 sec
  - Onboard and ground triggers
Swift Spacecraft & Instruments
Swift Instruments and Launch Vehicle
Burst Alert Telescope (BAT)

Coded Aperture Mask

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Coded Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>2.7 m²</td>
</tr>
<tr>
<td>Energy Range</td>
<td>15 - 150 keV (12-300 keV)</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>7 keV (5 keV)</td>
</tr>
<tr>
<td>Location Resolution</td>
<td>1-4 arcmin (1 - 4')</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1x10^-8 erg sec⁻¹ cm⁻²</td>
</tr>
<tr>
<td>Field of View</td>
<td>1.4 steradian</td>
</tr>
<tr>
<td>PSF</td>
<td>17 arcmin</td>
</tr>
<tr>
<td>Detector</td>
<td>32 000 CZT</td>
</tr>
<tr>
<td>Mode</td>
<td>Photon-Counting (Autonomous)</td>
</tr>
</tbody>
</table>
Coded-Aperture Imaging

Coded Aperture Mask Pattern

5 mm square Pb tiles

Flux 1

Flux 2

Counts

Mask

4 mm square CZT

- 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
<td>Wolter I</td>
</tr>
<tr>
<td>Energy Range</td>
<td>0.2-10 keV</td>
</tr>
<tr>
<td>Aperture</td>
<td>0.51 m</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$1 \times 10^{-14}$ erg sec$^{-1}$ cm$^{-2}$ in 10 000 s</td>
</tr>
<tr>
<td>Field of View</td>
<td>23.6 x 23.6 arcmin$^2$</td>
</tr>
<tr>
<td>PSF</td>
<td>18 arcsec FWHM @ 1.5 keV</td>
</tr>
<tr>
<td>Detector</td>
<td>e2v CCD-22</td>
</tr>
<tr>
<td>Mode</td>
<td>Autonomous</td>
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</table>
### Autonomous Operation of the XRT

<table>
<thead>
<tr>
<th>Method</th>
<th>Timing</th>
<th>Spectral Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image</td>
<td>Centroiding, 0.1 or 2.5 sec timing</td>
<td></td>
</tr>
<tr>
<td>Photodiode</td>
<td>10 μs timing, limited spectral capability</td>
<td></td>
</tr>
<tr>
<td>Windowed Timing</td>
<td>2.2 ms timing, med. res spectrum, 1-d pos.</td>
<td></td>
</tr>
<tr>
<td>Photon Counting</td>
<td>2.56 sec timing, med. res.spec, 2-d pos.</td>
<td></td>
</tr>
</tbody>
</table>

- **Slew**
  - Bias Row
  - Bias Map
  - Raw Image
  - Slew LrPD

- **is_in_10_arcmin**
  - PPT/TOO
    - PuPD
    - LrPD
    - WT
    - PC

- **is_settled**
  - AT
  - Imaging
    - GRB Position
    - PuPD
    - LrPD
    - WT Spectrum
    - LrPD Spectrum

- **Diagram Showing GRB 050714b**
  - Rate count/s vs Time (s) (154.2 sec after trigger)
  - WT mode
    - PC mode
The UV/Optical Telescope

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
<td>Modified Ritchey-Chrétien</td>
</tr>
<tr>
<td>Aperture</td>
<td>30 cm diameter</td>
</tr>
<tr>
<td>Wavelength</td>
<td>170-600 nm</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$m_B = 24.0$ in white light in 1000 s</td>
</tr>
<tr>
<td>Field of View</td>
<td>17 x 17 arcmin$^2$</td>
</tr>
<tr>
<td>PSF</td>
<td>0.9 arcsec FWHM @ 350 nm</td>
</tr>
<tr>
<td>Detector</td>
<td>MCP Intensified CCD</td>
</tr>
<tr>
<td>Mode</td>
<td>Photon Counting</td>
</tr>
</tbody>
</table>

Detector

Processing Electronics

Filter Wheel

Telescope Power Supply

Detector Power Supply

Digital Electronics Module (Prime)

Digital Electronics Module (Redundant)

Door

Baffle
10.8 ms readout of 17 x17 arcmin FoV
Onboard centroiding provides photon positions
Observing Scenario

1. Burst Alert Telescope triggers on GRB, calculates position to \( \sim 1 \) arcmin
2. Spacecraft autonomously slews to GRB position in 20–70 seconds
3. X-ray Telescope determines position to \( \sim 3 \) arcseconds
4. UV/Optical Telescope images field, transmits finding chart to ground
Data transmission

- Rapid dissemination of data to the world via TDRSS
  - Positions
  - Quicklook Lightcurves
  - Raw Images
  - Quicklook spectra
- Ground pass over Malindi to telemeter data from the solid state recorder on the spacecraft for ground processing
  - Event files
  - Processed lightcurves
  - Refined positions
  - Spectral characteristics
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
**BAT Bursts**

- Distributions from 104 bursts between 17 December 2004 - 11 January 2006
- Bi-modal the same as BATSE
- LogN-LogS shows higher sensitivity
**XRT Detections of BAT GRBs**

- Detected 103/109 with XRT (observed @ $T < 250$ ks)
  - Observed during prompt emission: 050117, 050717, 050820a, 050904, 060124, 060218
  - 72% Swift detections were prompt observations ($< 350$ s)
    - 82% have fast decline or a flare within first ~5 minutes
  - 32 have redshift measurements:
    - Average redshift: 2.2 (compared with 1.2 pre-swift bursts)
    - Highest redshift: 6.29 (highest GRB redshift on record)

- Detected 5/7 HETE bursts with XRT
- Detected 6/13 Integral bursts with XRT
XRT Positional Accuracy

GRB 041223
VLT
J-band
Dec 24.261

Afterglow
This work

Daniele Malesani – MISTICI collaboration

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

Berger et al. 2005

Average Accuracy 2.2"
UVOT Detections of BAT GRBs

- Detected 26/55 with UVOT
  - UVOT upper limits are quite faint and very early for many bursts
  - More ground-based detections (typically R, I, J, or K)
    - High z
      - Evidence in some cases
    - Dust extinction
      - Evidence supporting this for some bursts
    - Intrinsically Dark
      - Magnetic suppression?
GRB 050318: the first UVOT afterglow

Fig. 1.—Stacked UVOT-V filter image of the field with the transient source at RA = 08h 18m 51.5s, Dec = -46° 23' 43.7" (J2000) and a 3" BAT error circle and 6" XRT error circle overlaid. Total exposure time for the stacked image is 3,732s.
XRT Afterglow Summary

Compare GRB050215b with SAX/XTE/XMM/Chandra AG

SAX/XTE/XMM

XRF030723 (HED)

Time since trigger [s]

XRT Afterglow Types

From the XRT prompt observations, we see that there are at least 3 shapes of afterglow lightcurves:

- Type A
- Type B
- Type C
Type A afterglow: 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
\[ F_x \propto t^\alpha \]

\[ \alpha_1 = -0.27 \pm 0.10 \]

\[ \alpha_2 = -1.30 \pm 0.15 \]

\[ t_{\text{break}} = 1470 \text{ s} \]
Jet Break

Jet

Torus

Relativistic beaming:
\[ \theta \sim \Gamma^{-1} \]
**GRB 050128 spectrum**

Photon Index=$1-\beta = 1.66 \pm 0.07$

Galactic Absorbing Column = $N_H = 4.8 \times 10^{20} \text{ cm}^{-2}$ (for all three orbits)

\[
F_x = 2.2 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1}
\]

\[
F_x = 1.9 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}
\]

\[
F_x = 6.6 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}
\]
Type B afterglow: GRB 050319

Detected at 09:31:18 UT (T+ 225 s)

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

- 3.1 arcseconds from ROTSE counterpart
- Auto State - Determined GRB position onboard

GRB 050319 Spectrum

Photon index $= 1 - \beta = 2.6, 1.7$ and $1.8$ i.e. Starts softer and becomes harder

Galactic Absorbing Column $= N_H = 1.13 \times 10^{20}$ cm$^{-2}$ (for all three phases)

![Graph showing spectral energy distribution with annotations for different flux levels.](image-url)
High Latitude Emission
Type C: Giant X-ray Flare, GRB 050502b

GrB Fluence: $8 \times 10^{-7}$ ergs/cm$^2$

Flare Fluence: $9 \times 10^{-7}$ ergs/cm$^2$

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.
It is possible that all three types are related and we are viewing different parts of the lightcurve.

- Type A
- Type B
- Type C
GRB Models

Merging Neutron Stars

Old (few billion yrs)
Not in star-forming galaxies
Short Bursts

Hypernova

Young (few million yrs)
In star-forming galaxies
Long Bursts
GRB 050509b: First Short GRB Afterglow

$\tau_{90} = 0.04$ s, Fluence = $2 \times 10^{-8}$ 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

XRT error circle on VLT image. XRT position is 9.8" from a bright elliptical galaxy at $z=0.226$
GRB 050724: Flares in a Short GRB Afterglow

- Bright Complex lightcurve
- Associated with an elliptical galaxy
- Extended central engine activity
- Death call of a Neutron Star?

A Huge Explosion in the Early Universe

GRB 050904: Redshift of $z = 6.29$

- The most distant cosmic explosion ever observed
- Corresponds to 13 billion light years from Earth
- The Universe was just 700 - 750 million years old.
- Indicates the presence of massive stars only 700 million years after the big bang

Cusumano et al. 2005, Nature
Swifts Closest GRB: GRB 060218

- RA 03:21:39.71 Dec +16:52:02.6
- 25 times closer
- 100 times longer ~2000 seconds
- Surprisingly dim
- Early optical afterglow indicates a possible SN in the works
Summary

- Swift has exceeded every pre-launch predicted advance in GRB science
- Discovered the farthest GRB ever seen
- Identified counterparts to Short GRBs
- Discovered new GRBs at a rate of 100/year
- Explored a brand new time interval in GRB lightcurves
  - Revealing unpredicted phenomena of GRB flares
  - Revealing unpredicted rapid X-ray afterglow declines
- As the Swift catalogue increases, we expect new insights into GRB formation and environments
- Swift has conducted >20 000 successful slews to sources and is predicted to stay in orbit until 2022
- Public data release began April 5, 2005
  - http://swift.gsfc.nasa.gov/docs/swift/sdc/
XRT Collaborators

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- Valentina Laparola

* GSFC/USRA http://webpages.atlanticbb.net/~jeh22/

Data is public: http://swift.gsfc.nasa.gov/docs/swift/sdc/
Swift and Deep Impact Event

UVOT images in UVW1 filter

30 min before the impact  6 hours after the impact  34 hours after the impact

Swift Deep Impact Team