Gamma Ray Bursts

Julian Osborne
University of Leicester

The future of gamma-ray astronomy and the CTA
– Leicester  October 2010
Outline

GRB introduction
Swift observatory
GRB afterglows
Short GRBs
The most distant GRBs
The naked eye burst
Fermi results
The future
GRB introduction

Swift observatory

GRB afterglows

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The most distant GRBs

The naked eye burst

Fermi results

The first gamma-ray burst (1969)
Klebesadel et al 1973

The future
Gamma Ray Burst discovery

- Cold war at its height
- USA/Soviets think the other side may be testing nuclear bombs in space
- USA ‘Vela’ satellite programme designed to detect nuclear detonations
- Data indicate ‘interesting signals’ that do not originate from the Earth, Sun or Moon
Flash Forward

Over time, it became clear that nothing was clear.

- Some GRBs are relatively smooth, others spiky
- Durations range from 30 milliseconds to 1000 seconds
GRB recent history

CGRO BATSE
Sky distribution
1991-2000

BeppoSAX
X-ray afterglow discovery
1997
Discovery of host galaxies allowed measurement of distance and energy

Typical redshift (pre-Swift) $z \sim 1$
(i.e. distance $\sim 8$ billion light years)

Huge explosions: $E \sim 10^{51}$ ergs
(the Sun’s lifetime output in a few sec)

Signatures of black hole birth

Ultra-relativistic outflows ($0.99999c$)

Two types of burst: short and long
Collision with surroundings

Fireball Model of GRBs

Internal Shock
Collisions in different parts of the flow

The Flow decelerating into the surrounding medium

Collision with surroundings

Jet

GRB

Afterglow

\[ X \approx 10^{16} \text{ cm} \]

\[ 10^{14} \text{ cm} \]
Synchrotron model of GRB afterglow

Self-absorption break
Cooling break

0.24 days
0.63 days
1.26 days
2.50 days

GRB 030329
Willingale et al 2003
Long GRBs – Hypernovae

- Massive star (>30 M) dies – center collapses to BH
- Get Supernova + hyper-accreting disk “feeding Black Hole”
- In some cases get very fast jets (>0.9999c) emitted ⇒ GRB
Long GRB Hosts

- GRBs trace brightest regions in hosts
- Hosts are sub-luminous irregular galaxies

⇒ Concentrated in regions of most massive stars

⇒ Restricted to low metallicity galaxies

Fruchter 2005
Short GRBs – NS-NS merger?

- 2005 May 9 – first short burst located accurately on the sky
- In a (fairly) nearby elliptical galaxy not currently making stars
- No supernova – so what is it?
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Swift wins 2005 Best of What’s New award from Popular Science
What’s the problem? - The Time Gap

Swift

Beppo SAX data

X-ray Flux

Time (sec)

Brightness Factor 10,000

8 hrs
**What’s the solution? - The Swift Observatory**

**Burst Alert Telescope (BAT)**
- 15-150 keV coded mask imaging
- 2 sr field of view

**X-Ray Telescope (XRT)**
- 0.3-10 keV
- huge sensitivity range
- Arcsec GRB positions

**UV-Optical Telescope (UVOT)**
- Sub-arcsec position
- 22 mag sensitivity

**Spacecraft slews XRT & UVOT to GRB in <100 s**
Swift X-ray Afterglows – complicated

Curves & Breaks

GRB 050525A UVOT

GRB 050502B - XRT Lightcurve

GRB 050525A UVOT

GRB 050525A UVOT
**X-ray Afterglow features**

1. Light travel time effect from curved radiating surface (internal)
2. Plateau due to on-going energy injection to shock (external)
3. Flare due to central engine accretion event (internal)
4. Standard decay of shock (external)
5. Steeper decay as shock slows: after ‘jet-break’ (external)
Afterglow features: New implications

Existence of Plateau and Flares out to beyond 10,000 sec

- Many orders of magnitude longer than accretion disk dynamical timescale – something is holding up the accretion

Very few jet-breaks seen

- Jets narrower or wider than thought before Swift
- X-ray jet is narrower than optical jet
- Most X-ray afterglows too faint

Short GRB afterglows can have same features as long GRB afterglows

- Explosion dynamics & environment similar in spite of different origin
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2 Short GRBs - 2 Elliptical Hosts

GRB 050509B
- elliptical hosts
- low SF rates
- offset positions
- redshifts $z \sim 0.2$
  >> inconsistent with collapsar model
  >> supportive of NS-NS model

Gehrels et al. 2005

GRB 050724

Barthelmy et al. 2005

35 kpc offset

4 kpc offset
GRB 050724

BAT
- 250 ms hard spike
- $6 \times 10^{-7}$ erg/cm$^2$ fluence

Afterglow
- bright afterglow with flares
- detected by Chandra
- optical & radio

Host:
- Elliptical
- $L = 1.7 L^*$
- $z = 0.258$
- SFR $< 0.02 M_\odot$ yr$^{-1}$

Barthelmy et al. 2005
HETE-2 GRB 050709
z=0.16
HST images 1st optical short GRB afterglow

Swift GRB 080503
BAT light curve shows extended emission

Fox et al. 2005
Perley et al. 2009
# Short GRB Observations

<table>
<thead>
<tr>
<th>Name</th>
<th>Redshift</th>
<th>Afterglow</th>
<th>Host</th>
<th>$E_{\text{iso}}(15-150\text{keV})$</th>
<th>What might it be?</th>
</tr>
</thead>
<tbody>
<tr>
<td>050202</td>
<td>0.225</td>
<td>X</td>
<td>Elliptical</td>
<td>$1 \times 10^{48}$</td>
<td>NS-NS merger</td>
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<tr>
<td>050709*</td>
<td>0.161</td>
<td>X, O</td>
<td>SF galaxy</td>
<td>$6 \times 10^{49}$</td>
<td>NS-NS merger</td>
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<tr>
<td>050724</td>
<td>0.258</td>
<td>X, O, R</td>
<td>Elliptical</td>
<td>$3 \times 10^{50}$</td>
<td>NS-NS / NS-BH merger</td>
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<tr>
<td>050906</td>
<td>?</td>
<td>?</td>
<td>galaxy</td>
<td>$2 \times 10^{51}$</td>
<td>minimal afterglow</td>
</tr>
<tr>
<td>050925#</td>
<td>?</td>
<td>?</td>
<td>in gal. plane</td>
<td>?</td>
<td>possible new SGR</td>
</tr>
<tr>
<td>051210</td>
<td>?</td>
<td>?</td>
<td>cluster@</td>
<td>$2 \times 10^{48}$</td>
<td>NS-NS merger</td>
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<tr>
<td>051221</td>
<td>0.547</td>
<td>X, O, R</td>
<td>SF galaxy</td>
<td>$9 \times 10^{50}$</td>
<td>-</td>
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<tr>
<td>060121*</td>
<td>?</td>
<td>?</td>
<td>cluster</td>
<td>-</td>
<td>minimal afterglow</td>
</tr>
<tr>
<td>060313</td>
<td>?</td>
<td>?</td>
<td>cluster@</td>
<td>-</td>
<td>? NS-NS merger</td>
</tr>
</tbody>
</table>

* HETE GRB
# soft spectrum
@ galaxy in cluster

### Swift GRBs

![Swift GRBs](image)

- $E_{\text{iso}}$ (erg)
- $T_{90} / (1+z)$ (s)

long GRBs
short GRBs
Less beaming in Short GRBs?

GRB 050709 – no jet break, $\Theta > 23^\circ$
Watson et al. 2006

Jet opening angles and limits (blue)
Watson et al. 2006
Short GRB Summary

Strong evidence that short GRBs generally associated with old stellar populations

Rapid fluctuations imply compact source origin.
Energetics suggest collapse to BH

Could be NS-NS or NS-BH mergers, or accretion-induced collapse of NS.

If NS-NS, some systems may be exchange captures in globular clusters

Gravitational Waves:

2015: A-LIGO detection rate of $6-30 \text{ yr}^{-1}$

Thorne et al.
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The clearing of the fog – re-ionisation of the Universe
**GRB 050904 – The Far Universe**

Redshift $z = 6.29$

- distance $\sim 12.8$ billion light yr
- Universe $6.5\%$ of current age

$T_{90} = 225$ sec

$S (15-150 \text{ keV}) = 5.4 \times 10^{-6} \text{ erg cm}^{-2}$

$E_{iso} = 3.8 \times 10^{53}$ erg

**X-ray Afterglow**

Cusumano et al. 2005

**Prompt**

**GRB 050904**

**Typical GRB**

**Flux x100 of high-z luminous X-ray AGN**
GRB 050904 Optical Spectroscopy

- Hydrogen Lyman absorption in the IR
- Optically bright: J mag = 17.6 at 3.5 hours
- Very low metallicity

Subaru Spectroscopy

Kawai et al. 2006

Berger et al. 2006
GRB 090423 – the record holder

Redshift = 8.2
Universe 630 Myr old (4.6% of current age)
$T_{90} = 10.3$ sec
$E_{\text{iso}} = 1 \times 10^{53}$ erg

UKIRT & Gemini imaging implies $z > 7.8$

The largest facilities will be needed

Tanvir et al. 2009 Nature. VLT ISAAC spectrum
Swift GRB Distance Distribution

Gehrels, Ramirez-Ruiz & Fox 2009
“GRBs are the new QSOs”

Redshift records

Although current record-holder is a $z=8.56$ galaxy at in the HST ultra-deep field (Lehnert et al 2010)
Bright Across the E-M Spectrum

<table>
<thead>
<tr>
<th>$z$</th>
<th>GRB</th>
<th>Optical Brightness</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>090423</td>
<td>K = 20 @ 20 min</td>
</tr>
<tr>
<td>6.7</td>
<td>080813</td>
<td>K = 19 @ 10 min</td>
</tr>
<tr>
<td>6.29</td>
<td>050904</td>
<td>J = 18 @ 3 hrs</td>
</tr>
<tr>
<td>5.6</td>
<td>060927</td>
<td>I = 16 @ 2 min</td>
</tr>
<tr>
<td>5.3</td>
<td>050814</td>
<td>K = 18 @ 23 hrs</td>
</tr>
<tr>
<td>5.11</td>
<td>060522</td>
<td>R = 21 @ 1.5 hrs</td>
</tr>
</tbody>
</table>

GRBs: brightest high-z sources

GRB 090423 $z = 8.2$ has X-ray light curve like closer GRBs

Salvaterra et al. 2009
### History of the Universe

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>-</td>
<td>Big Bang - Hot ionized gas</td>
</tr>
<tr>
<td>100</td>
<td>17 Myr</td>
<td>The Universe becomes neutral and opaque</td>
</tr>
<tr>
<td>10</td>
<td>480 Myr</td>
<td>Stars and galaxies form, Reionization starts</td>
</tr>
<tr>
<td>8.2</td>
<td></td>
<td>Cosmic Renaissance, Dark Ages end</td>
</tr>
<tr>
<td>5</td>
<td>1.2 Gyr</td>
<td>Reionization complete, Galaxies evolve</td>
</tr>
<tr>
<td>0.5</td>
<td>8.7 Gyr</td>
<td>Solar System forms</td>
</tr>
<tr>
<td>0</td>
<td>13.7 Gyr</td>
<td></td>
</tr>
</tbody>
</table>
The first naked eye gamma-ray burst

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Arthur C Clarke
1917 – 2008
The first ‘naked eye’ burst - GRB 080319B

The brightest and most energetic burst seen by Swift

The first burst that could have been seen without optical aid (mag 5.6)

\[ z = 0.94 \text{ (7.5 billion light yrs)} \]
**GRB 080319B**

Pi of the Sky – stares at a large fraction of the sky all the time

- 2x 85 mm lenses with CCD cameras
- FOV: 22x22 deg
- 10 sec exposures - real-time flash search

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**"Pi of the Sky" observation of GRB 080319B**

- Brightness limits
- Flash brightness

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Pi of the Sky
Wide-field monitoring system: TORTORA

Telescopio Ottimizzato per la Ricerca dei Transienti Ottici Rapidi

Two-telescope complex:
- independent detection
- automatic study

24x32 deg FOV
mag. lim. ~10.5
La-Silla, Chile
mounted on REM
since 2006
GRB 080319B
The “naked-eye” GRB

“Star explodes halfway across the Universe” (CNN, 21/03/08)

Did this amazing GRB tell us about all GRBs or is it just weird?
Corrected for distance, this was the brightest burst seen at optical wavelengths.

The brightest bursts seem to have an additional short-lived component, by 1 day the range of brightness is much less.

Is this a ‘reverse shock’?

Bloom et al.
Racusin et al. 2008 – 2-jet model:
Narrow (0.4°); Wide (8°)
Origin of bright optical light is unclear (e.g. Zou et al.; Kumar & Narayan; Kumar & Panaitescu etc.)
The value of GRBs for exploring the Universe

GRBs are much more luminous than the most energetic quasars and supernovae

They could be seen in the ‘dark ages’, if they exist then (and are not too obscured)

In our Galaxy this burst would have appeared brighter than the Sun!

Bloom et al.
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LAT: 100 MeV – 100 GeV
GBM: 8 keV – 40 MeV
## Fermi LAT GRBs

<table>
<thead>
<tr>
<th>GRB</th>
<th>Duration</th>
<th>Redshift</th>
<th>Notes</th>
<th>Detector</th>
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<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>
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<td>extended emission</td>
<td>Swift</td>
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<tr>
<td>GRB 081215A</td>
<td>7.7 s</td>
<td></td>
<td>Swift</td>
<td></td>
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<tr>
<td>GRB 090217</td>
<td>33 s</td>
<td></td>
<td></td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 090323</td>
<td>150 s</td>
<td>z = 3.57</td>
<td>extended emission</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 090328</td>
<td>100 s</td>
<td>z = 0.736</td>
<td>extended emission</td>
<td>Swift</td>
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<tr>
<td><strong>GRB 090510</strong></td>
<td>2.1 s</td>
<td>z = 0.903</td>
<td>extended emission</td>
<td>Swift</td>
</tr>
<tr>
<td>GRB 090626</td>
<td>70 s</td>
<td></td>
<td>extended emission</td>
<td></td>
</tr>
<tr>
<td>GRB 090902B</td>
<td>21 s</td>
<td>z = 1.822</td>
<td>34 GeV photon</td>
<td>Swift</td>
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<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></td>
</tr>
<tr>
<td>GRB 100116A</td>
<td>110 s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRB 100225A</td>
<td>13 s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRB 100414A</td>
<td>26 s</td>
<td></td>
<td></td>
<td>Swift</td>
</tr>
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</table>
### Fermi LAT GRBs

<table>
<thead>
<tr>
<th>GRB</th>
<th>Duration</th>
<th>Redshift</th>
<th>Emission Type</th>
<th>Telescopes</th>
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<td>z = 0.736</td>
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<td><strong>GRB 090510</strong></td>
<td>2.1 s</td>
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<tr>
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<td>GRB 091003</td>
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<td>GRB 091031</td>
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<td>26 s</td>
<td></td>
<td></td>
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</tbody>
</table>

\[(1+z)E = 96 \text{ GeV!}\]
Delayed HE Emission - GRB 090510

Short GRB

\[ z = 0.903 \quad 7.3 \text{ Gyr light travel} \]

Extended emission

Lag in MeV/GeV onset

Lorentz factor (jet) > 1000
\((\gamma\gamma)\) absorption argument

Lorentz invariance violation limits:
- No observed dispersion
- \(|\Delta t / \Delta E| < 30\text{ms/GeV}\)
- Quantum Gravity mass scale above Planck mass (most QG predict the opposite)

Abdo et al. Nature 2009
GRB 090510 - High Energy Component

LAT extension into afterglow phase

LAT spectral evolution

LAT

XRT

UVOT

BAT

Flux

Time

de Pasquale et al. 2010

Energy

Abdo et al. 2009
Akermann et al. 2010
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The Future is Bright

- Fermi & AGILE & TeV (high energy $\gamma$-rays)
- new HST & JWST (2013) (opt & IR)
- PTF & PanSTARRS & LSST (optical wide-field)
- EVLA & LOFAR & ALMA (radio (m - mm))
- ICECUBE (2009-2011) (neutrinos)
- LIGO (2014-aLIGO) (gravitational wave)
- SVOM Chinese-French (GRBs hard X-ray & opt)
- NASA Explorer & ESA M3 candidates (GRBs)
- Swift until 2020
- JWST sensitivity
- IR Afterglow
- Bromm & Loeb (2007)
- SVOM
- UK LOFAR station opened Sept 2010
Follow-on from Swift:

- better energy coverage, pointing strategy (anti-Sun) and lower trigger energy range (4-300keV)

- Find nearby X-ray bright, low L GRBs (SN connection)

- Find high-redshift GRBs (faster/deeper optical limits)

- Link to non-EM radiation observations (adv. LIGO etc.)

- Launch planned 2015/16
NASA Explorer mission proposals

LOBSTER: focussing soft X-ray GRB detectors + IR spectroscopy: redshift estimate

JANUS: coded mask GRB detector + IR spectroscopy: redshift estimate
Low-energy section
energy threshold of some 10 GeV

Core array:
mCrab sensitivity in the 100 GeV–10 TeV domain

High-energy section
10 km² area at multi-TeV energies

CTA
The VHE Variable Universe with CTA

Fermi

1 min

1 hour

10 hours

100 hours

GRBs, AGN, microquasars...

CTA has ~km² effective area

CTA

$E \times \text{Integral Flux Sens. (erg cm}^{-2} \text{s}^{-1})$

$\log_{10}(\text{Energy/TeV})$
GRB Science with CTA

• Much greater photon statistics than Fermi
  • very good broadband spectra, spectral variability

• Energetics
• Bulk Lorentz factor limits/measurements from intrinsic $\tau_{\gamma\gamma}$

• Origin of prompt emission (int. shock? photosph.? B recon.?)
• Afterglow physics (steep/shallow phase, reverse shock…)
  • jet physics, environment, progenitor

• Probe UHECR/ HE neutrino production from hadronic components (p\gamma cascade, p synchrotron...)
  • synergy with Auger/TA, IceCube/KM3NeT…
• Probe high-z EBL

• Probe fundamental physics (nonstd. particles, LIV…)

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Thank you