A Decade of Short-duration Gamma-ray Burst Afterglows

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Einstein Fellows Symposium, 10.28.2014
Central engine

Prompt emission

Afterglow

Gamma-rays

X-ray
Optical
Near-IR
Radio

Figure adapted from Gehrels et al. 2007
Central engine

Gammar-rays

Prompt emission

Afterglow

Figure adapted from Gehrels et al. 2007
Motivation

Characterize short GRBs on parsec scales: kinetic energy density opening angle

Figure adapted from Gehrels et al. 2007
Outline

Background

Afterglow census

Explosion properties

Application to gravitational waves
One decade ago...
One decade ago…

October 27, 2004
One decade ago...

- Rapid slewing
- Multi-wavelength
- Precise localization
Two populations of bursts

Credit: NASA
Two populations of bursts

Credit: NASA
Two populations of bursts

Credit: NASA

SHORT, \( t < 2 \text{ sec} \)

LONG, \( t > 2 \text{ sec} \)
The first short GRB afterglows

Fox et al. 2005

$\Delta T < 48 \text{ hours}$

GRB 050709

Hubble Space Telescope
The first short GRB afterglows

ΔT < 48 hours

~23 mag @ 10 hr after burst discovery
The multi-wavelength Target-of-Opportunity afterglow chase

Chandra

XMM-Newton
The multi-wavelength Target-of-Opportunity afterglow chase

Chandra
Magellan (Chile)
MMTO (Arizona)
LBT (Arizona)

XMM-Newton
The multi-wavelength Target-of-Opportunity afterglow chase

Chandra
Magellan (Chile)
MMTO (Arizona)
LBT (Arizona)
XMM-Newton
UKIRT (Hawaii)
The multi-wavelength Target-of-Opportunity afterglow chase

Chandra
Magellan (Chile)
MMTO (Arizona)
LBT (Arizona)

XMM-Newton
UKIRT (Hawaii)
VLA (New Mexico)
Afterglow census
Why do we need multi-wavelength?
Why do we need multi-wavelength?

\[ \log(\text{Flux}) \]

\[ \log(\text{Frequency}) \]

\[ E_{K,\text{iso}, n} \]

\[ E_{K,\text{iso}, n} \]

\[ E_{K,\text{iso}} \]
Short GRB X-ray afterglows
Short GRB X-ray afterglows

60/78 detections
Short GRB optical afterglows
Short GRB optical afterglows

![Graph showing optical AB magnitude against time after burst (days)].

- **Detection**
- **3σ upper limit**
Short GRB optical afterglows

Optical

6-10 m

26/72 detections
Short GRB radio afterglows

Radio Flux Density (µJy) vs. Time after Burst $\delta t$ (days)

- Detection
- $3\sigma$ upper limit
Short GRB radio afterglows

Radio Flux Density (µJy) vs. Time after Burst $\delta t$ (days)

- Detection
- 3σ upper limit
Short GRB radio afterglows

<table>
<thead>
<tr>
<th>Radio Flux Density ($\mu$Jy)</th>
<th>Time after Burst $\delta t$ (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$10^{0}$</td>
<td></td>
</tr>
<tr>
<td>$10^{1}$</td>
<td></td>
</tr>
<tr>
<td>$10^{2}$</td>
<td></td>
</tr>
<tr>
<td>$10^{3}$</td>
<td></td>
</tr>
</tbody>
</table>

- 3/50 detections
- Detection
- $3\sigma$ upper limit
Afterglow census

log(\text{Flux})

log(\text{Frequency})
Afterglow census

log(Flux) vs. log(Frequency)

Radio

Optical Near-IR

X-ray

$E_{K,iso}$, $n$

$E_{K,iso}$, $n$

$E_{K,iso}$

# Detected / # Observed
What can the lack of afterglow detections tell us about their Explosion Properties?
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An example: GRB 120804A

X-ray and optical afterglows, radio non-detection
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X-ray and optical afterglows, radio non-detection
An example: GRB 120804A

X-ray and optical afterglows, radio non-detection

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Plot showing the relationship between $E_{K,iso}$ (erg) and $n$ (cm$^{-3}$) for GRB 120804A. The plot indicates a range of values for $E_{K,iso}$ from $10^{51}$ to $10^{54}$ erg, and $n$ from $10^{-4}$ to $10^0$ cm$^{-3}$. The equation $v_c < v$, $\varepsilon = 0.1$ is also noted.
An example: GRB 120804A

X-ray and optical afterglows, radio non-detection
An example: GRB 120804A

X-ray and optical afterglows, radio non-detection
An example: GRB 120804A

X-ray and optical afterglows, radio non-detection

$E_{K,\text{iso}} = 1.1^{+0.3}_{-0.2} \times 10^{52} \text{ erg}$

$n = 3.2^{+3.1}_{-1.5} \times 10^{-3} \text{ cm}^{-3}$
Each burst has its own story...
Population explosion properties

\[ <n> = 4.1 \times 10^{-3} \text{ cm}^{-3} \]

95% is \(< 1 \text{ cm}^{-3}\)
Population explosion properties

\[<n> = 4.1 \times 10^{-3} \text{ cm}^{-3}\]

95\% is < 1 cm\(^{-3}\)

\[<E_{K,\text{iso}} > = 1.7 \times 10^{51} \text{ erg}\]

No trend with elliptical vs. star-forming host
highly collimated

spherical
if $\theta_{\text{jet}} \sim 10$ deg,

$E_{\text{true}} \sim 10^{49}$ erg

$R_{\text{true}} \sim 1000$ Gpc$^{-3}$ yr$^{-1}$
Application to gravitational wave counterparts
For a compact object merger at 200 Mpc...
For a compact object merger at 200 Mpc...

...for an observer angle of twice the opening angle of the jet...
For a compact object merger at 200 Mpc...

...for an observer angle of twice the opening angle of the jet...

...with typical inputs from observed short GRBs...

\[ n \sim 10^{-3} \text{ cm}^{-3}, \ E \sim 10^{49} \text{ erg} \]
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...the optical light curve will peak at 24.5 mag \((10^{40} \text{ erg s}^{-1})\).
For a compact object merger at 200 Mpc…

…for an observer angle of twice the opening angle of the jet…

…with typical inputs from observed short GRBs…

\[ n \sim 10^{-3} \text{ cm}^{-3}, \quad E \sim 10^{49} \text{ erg} \]

…the optical light curve will peak at 24.5 mag (10^{40} \text{ erg s}^{-1}). Yikes.
Trends with host properties?
Trends with host properties?
Trends with host properties?

Star-forming Elliptical
Trends with host properties?

Star-forming Elliptical

\[ \delta R \]