Observations of Gamma-Ray Bursts and X-Ray Flashes with High Energy Transient Explorer 2 (HETE-2)

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Outline

- Issues on gamma-ray bursts
- Description of HETE-2
- Results
  - Rapid notification and early afterglow light curves
  - Optically dark GRBs
  - Supernova-GRB connection
  - X-ray rich GRBs and X-ray flashes
OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from ~10^{-5} ergs cm^{-2} to ~2 \times 10^{-4} ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars
Gamma-Ray Bursts (GRBs)

- Bright in the hard X ray to the $\gamma$ ray energy band (50-300 keV)
- “Spiky” light curves
- Long / short duration GRBs
- Uniform sky distribution and lack of very faint GRBs
- Discovery of afterglow
- Redshift of GRB, $z \sim 1$

Compton Gamma-Ray Observatory (CGRO)
Burst And Transient Source Experiment (BATSE)

BeppoSAX
(WFC / GRBM / NFI)
(http://heasarc.gsfc.nasa.gov/docs/sax/gallery/inst.html)

Discovery of afterglow
Breakthrough 30 years after the discovery:

Discovery of X-ray afterglow by BeppoSAX (GRB970228)

BeppoSAX observation of GRB970228 field

- SAX MECS: 1997 Feb 28, Exposure: 14,534 s
- 6°20'39'' E 5°02'00'' N 5°01'42'' W 6°01'16''

1997 Feb 28
1997 Mar 3

8 hours
3 days
Optical Afterglow of GRBs

Redshifts (distance, age)
Questions answered

- X-ray and/or optical afterglows found for long soft GRBs
- Consistent with Cosmological Fireball model
  - Power-law decay: days—months duration of afterglows
  - Broadband spectra (radio — X-ray)
- Redshifts determined by spectral features
  - $z \sim 0.4—4.5$ (1 typical)
- Host galaxies identified
  - GRB in galaxies, but off-center (not an AGN)
  - Star forming galaxies
- Beaming (Jet-like geometry) $\sim 1/100$
  - True energy $\sim 10^{51}$ ergs
Origin?

- Collapse of massive star
  - Extreme case of core-collapse SN
  - Rate OK: only 1 in $10^{4-5}$ of SN
  - Consistent with locations in SFR
- Neutron star merger
  - Rate roughly OK
  - Predicts locations out of galaxy disk
Remaining Questions

- Nature of GRBs with no optical afterglows
  - Short hard GRB
  - X-ray rich GRB (X-ray Flash)
  - Dark Burst
- First one hour
- Light curve variation on short time scales
- Emission lines in X-ray afterglow
HETE-2: Goals and Program

~ FIRST DEDICATED $\gamma$-RAY BURST SATELLITE ~

GOALS:
- Locate GRBs Accurately ($\sim 10'$ — 10'"
- Distribute Locations Rapidly ($\leq 10$ s delay)
- Measure multi-wavelength spectra
  
  [ Soft X-ray $\sim \gamma$-ray; 0.5 keV $\sim 500$ keV ]

PROGRAM:
- University-managed; NASA + Japan + France
  + Italy + India + Brazil
- University-constructed spacecraft
- 1/3 cost of NASA Small Explorer (SMEX)
**HETE-2 Instruments**

**Spacecraft**  
MIT

- **Uplink**  
  - S-band (2.272 GHz) 250 kbps  
  - VHF (137.96 MHz) 300 bps
- **Downlink**  
  - S-band (2.092 GHz) 31 kbps

**Weight** 124 kg  
**Height** 89 cm  
**Width** 66 cm  
**Orbit** Alt. 625 km  
**Equatorial life** > 2 years (3 years now)  
**Attitude** anti-solar

**Instruments**

- **WXM**  
- **RIKEN/LANL**  
- **FREGATE**  
- **CESR**  
- **SXC**  
- **ACS/OPT**  
- **Camera** MIT
Characteristics of HETE-2

(1) Real time localization of GRB for the ground follow-up observers
(2) Broad band spectroscopy (2-400 keV) of the prompt emission of GRB

Wide-field X-ray Monitor (WXM)  French Gamma-ray Telescope (FREGATE)

- WXM (2-25 keV) + FREGATE (7-400 keV)
Effective area curve

- 2-25 keV
- 7-400 keV

FREGATE (4 detectors)
WXM (4 detectors, with mask)
SXC (2 CCDs, with mask)
GRB Alert System of HETE-2

Primary Ground Stations (Singapore, Kwajalein, and Cayenne)

Gamma-Ray Burst

VHF

S band

Data and Commands

Localization Alerts

Secondary ground stations

Internet

Control Center (MIT)

GCN (Gamma-Ray Burst Coordinate Network)

Observatories
Delay of Location Alerts

Delay (min)

2000 2001 2002 2003


no OT
OT
Flight loc
Major results by HETE-2:
Very early afterglow light curves

- Made possible by HETE-2
- Variety in intensity, slope, and color
- Dense observation
  - wiggles and bumps
GRB021004 localization alert

Elaplsed Time | Uncertainty
--- | ---
48 s | Flight Location 60 arcmin
74 min | Ground Analysis 20 arcmin
154 min | SXC Gnd Analysis 4 arcmin
- earlier by two orders of mag
  - capture bright phase
- "movie" vs. "snapshots"
  - structure in light curve
“Wiggles and bumps”

circumstellar shells

repeated energy injection

SN1987A
Optically dark GRBs

- No optical transients found for about half of the well-localized bursts
- Three explanations of “optically dark” GRBs have been discussed:
  - Optical afterglows are extinguished by dust (star forming region) in the host galaxy (see, e.g., Reichart and Price 2001)
  - Some optical afterglows are intrinsically very faint (see, e.g., Fynbo et al. 2001; Berger et al. 2002)
  - GRBs lie at very high redshifts (Lamb and Reichart 2000)
GRB021211
location disseminated in 22 s

2— 5 keV
2— 5 keV
5—10 keV
10—25 keV
6—15 keV
15—30 keV
30—85 keV
85—400 keV
Rapid Response

- **R=14.1** at **t=60 s**
  - GCN#1738 Wood-Vasey et al. (RAPTOR)

- **R=15.2** at **t=143s**
  - GCN#1736 H.S.Park et al. (Super-LOTIS)

- **R=15.3** at **t=171s**
  - GCN#1737 Li et al. (KAIT)
GRB021211: Afterglow Light Curve Relative to Those of Other GRBs

Fox et al. (2003)
GRB030115 Infrared afterglow

Levan et al. 2003

Very high z
Local extinction (SFR?)

IRSF/SIRIUS Kato, et al.

Subaru FOCAS Tsuru et al. I-band
HETE- 2 is Solving Mystery of “Optically Dark” GRBs

- Rapid follow-up observations of HETE- 2—localized burst GRB030115 show that this burst is best case to date of extinction by dust.

- Rapid follow-up observations of HETE- 2—localized burst GRB021211 show that this burst is “optically dim” – without rapid follow-up would have been classified as “optically dark”.

- Very high-z events yet to be detected.
Supernova connection
**SN1998bw**: Type 1c SN at $z=0.008$
found at the position of GRB 980425
But unusually powerful

Galama et al.
SN1998bw = GRB980425?

- GRB/ SN: time and location consistent
- Most radio- luminous SN
- Radio obs suggests relativistic expansion
- Unusual optical spectrum
- Unusual optical light curve

- Luminosity: $10^{-6}$ of typical GRB
- SN energy $>>$ GRB energy
  - (no “GRB afterglow” seen)

Maybe associated, but different from ordinary GRB
“Monster GRB”
GRB030329

The brightest GRB localized by HETE-2

Vanderspek et al. (2003)
Localization by HETE-2

- Trigger: 11:37:14
- Alert: 11:38:41
- SXC: 12:50:24 (+73 min)
- OT: 12:52:09 (+75 min)

Torii #1986
Peterson #1985

- The fluence of the burst $\sim 1 \times 10^{-4}$ ergs cm$^{-2}$
- Peak flux over 1.2 s was $> 7 \times 10^{-6}$ ergs cm$^{-2}$ s$^{-1}$ (i.e., $> 100 \times$ Crab flux in the same energy band)
- X-ray afterglow: 7 mCrab (RXTE, +5 hr)

$z = 0.1675 \Leftrightarrow$ probability of detecting a GRB this close by is $\sim 1/3000$
=> unlikely that HETE-2 or Swift will see another such event
in the city light ...
30 cm Telescope on the Tokyo Tech roof
Images taken at Tokyo Tech

- 21:43: $t_0 + 1.1$ hr
- 23:47: $t_0 + 3.2$ hr
- 01:54: $t_0 + 5.3$ hr
- 03:18: $t_0 + 6.5$ hr
Tokyo Tech data + GCN

Light curve of the optical afterglow of GRB 030329

$\alpha \sim -0.9$

$\alpha \sim -1.2$

$\alpha \sim -1.9$

Sato et al. 2003
Supernova connection established

Stanek et al. 2003
also Hjorth et al. 2003
Kawabata et al. 2003
Lipkin et al. 2003
GRB030329: Implications

- HETE-2—localized burst GRB030329/SN 2003dh confirms the GRB – SN connection

- Implications:
  - We must understand Type Ib/Ic core collapse SNe in order to understand GRBs
  - Conversely, we must understand GRBs in order to fully understand Type Ib/Ic core collapse SNe
  - Result strengthens the expectation that GRBs occur out to $z \sim 20$, and are therefore a powerful probe of the early universe
GRBs Are Easily Detectable at $z \sim 20$

Sample of 15 GRBs with known redshifts

flux scaled to larger redshift

Lamb & Reichart (2000; see also Ciardi and Loeb 2000)
X-ray rich GRBs and XRFs (X-ray flash)
Empirical spectral models of GRBs

Band function

\[ dN/dE = E^\alpha \exp \left( -E/E_0 \right) \]

\[ E_0 = E_{\text{peak}} / (2 + \alpha) \]

\[ E_{\text{break}} = (\alpha - \beta) E_0 \]

Energy
Spectral parameters of GRBs (BATSE)

(BATSE spectral catalog, Preece et al. 2000)

Band function

$\alpha$

$E_p$

$\beta \sim -2.5$
X- Ray Flashes (XRFs) and X-ray rich GRBs
(Ginga and BeppoSAX WFC)

Ginga (Strohmayer et al. 1998)

WFC / BATSE (Kippen et al. 2002)

- Number of events
- $\log E_p [\text{keV}]$
- $P_{1024}$ (ph cm$^{-2}$ s$^{-1}$)

(22 GRBs)
“Standard energy” Frail’s relation

\[
E_\gamma = (1.33 \pm 0.07) \times 10^{51} \text{ erg}
\]

(Frail et al. 2001)  
(Bloom et al. 2003)
Spectra of GRB prompt emission
-- broken power-law

- $E_p = \text{a few 100 keV in BATSE sample}$

Mallozzi et al. 1995

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$\nu F_\nu$ vs. Energy

Bright 20%

dimmest 20%

Mallozzi et al. 1995
XRF010213

- Burst time: 13 February 2001 12:35:35 UT (4 months after the launch)
- Burst location: (R.A., Dec.) = (10h31m26s, 5°30'30'') (J2000) with a 95% error radius of 30'

Burst Properties

- Duration: 20.9 s (T90 WXM 2-25 keV band)
- X-ray / γ-ray fluence ratio:
  \[ S (2-30 \text{ keV}) / S (30-400 \text{ keV}) = 13.5 \]
- Total fluence (2 - 30 keV): \((6.3 \pm 0.6) \times 10^{-7} \text{ erg cm}^{-2}\)
- Peak flux
- No afterglow was found.
  (Boer et al., Hudec et al., Henden et al., Berger et al. and Zhu et al.)
XRF010213

(a) 2–5 keV WXM
(b) 5–10 keV WXM
(c) 10–17 keV WXM
(d) 17–25 keV WXM
(e) 6–40 keV FREGATE
(f) 32–400 keV FREGATE

Counts/s

Time (s)

Sakamoto et al. 2004
Definition of XRF/ XRR/ GRB

Fluence in 2-30 keV : $S_X$, Fluence in 30-400 keV : $S_\gamma$
(in the best fit spectral model)

\[
\begin{align*}
\log (S_X / S_\gamma) &> 0 & \text{XRF} \\
-0.5 < \log (S_X / S_\gamma) &\leq 0 & \text{XRR} \\
\log (S_X / S_\gamma) &\leq -0.5 & \text{GRB}
\end{align*}
\]

XRF : X-ray flash
XRR : X-ray rich GRB
GRB : Hard GRB
GRB020903

Trigger time: 10:05:37.96 on 2002 September 3

Burst properties:
- Duration (2-10 keV): 4.9 s (T50), 9.8 s (T90)
- X-ray / γ-ray fluence ratio: \( S(2-30 \text{ keV}) / S(30-400 \text{ keV}) = 5.6 \)
- Peak flux (1s, 2-10 keV): \( (2.2^{+0.8}_{-0.8}) \) ph cm\(^{-2}\) s\(^{-1}\)
- Total fluence (2-10 keV): \( (5.9^{+1.4}_{-1.4}) \times 10^{-8} \text{ erg cm}^{-2} \)

Afterglow candidate:
- Optical transient (Palomar 200-inch, Soderberg et al.)
- Redshift of underlying galaxy \( z = 0.25 \pm 0.01 \) (Soderberg et al., Chornock & Filippenko)
- Radio source at OT position (VLA, Berger et al.)
- Host galaxy is an irregular galaxy (HST, Levan et al.)

Sakamoto et al. 2003
GRB020903

Trigger time:
10:05:37.96 on 2002 September 3

Burst properties:
- Duration (2-10 keV): 4.9 s (T50), 9.8 s (T90)
- X-ray / γ–ray fluence ratio:
  \[ \frac{S(2-30 \text{ keV})}{S(30-400 \text{ keV})} = 5.6 \]
- Peak flux (1s, 2-10 keV): (2.2 ± 0.8) ph cm\(^{-2}\) s\(^{-1}\)
- Total fluence (2-10 keV): (5.9 ± 1.4) \(\times 10^{-8}\) erg cm\(^{-2}\)

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- Optical transient (Palomar 200-inch, Soderberg et al.)
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  (Soderberg et al., Chornock & Filippenko)
- Radio source at OT position (VLA, Berger et al.)
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GRB020903

Soderberg et al 2003
Constrain Ep of GRB020903

WXM spectrum

- power-law model with photon index $\alpha = -2.8$
  ($\alpha < -2$ at 99.3% confidence level)
- $\text{Ep}$ lies near or below 2 keV (WXM lower energy boundary)

Constrained Band function

- parameterized $\text{Ep}$ and $\beta$ (high-energy index)
- Only the high-energy part of the Band function is allowed to produce a pure power-law spectrum.

Ep of GRB020903 using the *constrained* Band function

- $1.1 \text{ keV} < \text{Ep} < 3.6 \text{ keV}, 68\%$
- $\text{Ep} < 4.1 \text{ keV}, 95\%$
- $\text{Ep} < 5.0 \text{ keV}, 99.7\%$

Sakamoto et al. 2003
Summary (1)

- XRFs/XRRs are similar to hard GRBs
  - duration
  - temporal profile
  - spectral softening

- The lower $E_{\text{peak}}$ energies for XRFs/XRRs
  (No difference in $\alpha$ and $\beta$)
  - Six XRFs with $E_{\text{peak}}$ of a few keV

- The afterglow of XRFs are generally very faint
Fluence ratio distribution

![Graph showing fluence ratio distribution with categories Hard GRB, XRR, and XRF.](chart.png)
Comparison with WFC/BATSE XRF
E_{peak} distribution

HETE

WFC/BATSE
Analysis

HETE localized GRBs
1) the burst signal is seen in both WXM and FREGATE
2) both WXM and FREGATE data have enough statistics to carry out the spectral analysis

- HETE GRBs from February 2001 to September 2003
- Time-average spectral analysis

45 GRBs

15 X-ray flashes
20 X-ray rich GRBs
10 hard GRBs
2-30 keV - 30-400 keV fluence

2 - 30 keV energy fluence (10^{-7} \text{ erg cm}^{-2})

30 - 400 keV energy fluence (10^{-7} \text{ erg cm}^{-2})

Band function

Cutoff power-law

Power-law

Sakamoto 2004
Comparison with WFC/BATSE XRF

$E_{\text{peak}}$ vs. 50-300 keV peak flux

$E_{\text{peak}} \propto P^{0.379}$

WFC/BATSE

HETE

$r = 0.790$

Sakamoto 2004
SED peak energy (at source) vs. isotropic radiated energy

BeppoSAX events by Amati et al. 2002

\[ E_p \propto \sqrt{E_{rad}} \]

Energy

\( vF_v \)

\( E_p \)
“Extended” Amati’s relation
(Amati et al. 2002; Sakamoto et al. 2004; Lamb et al. 2004)

\[ E_{\text{peak}}^{\text{src}} \propto E_{\text{iso}}^{0.5} \]
Summary (2)

- No boundaries between XRFs, XRRs, and hard GRBs.

- The $E_{\text{peak}}$ energy seems to be distributed in much lower energy, unlike the BATSE $E_{\text{peak}}$ distribution.

- $E_{\text{peak}} \propto$ time-average $\gamma$–ray flux
  \[ \propto \gamma$–ray peak flux \]

- “Extended” Amati’s relation
  $E_{\text{peak}}^{\text{src}} \propto E_{\text{iso}}^{0.5}$ (from XRF to GRB)
Sky distribution of XRF/ XRR/ GRB

All GRBs are populated uniformly in the sky

X-ray flash
X-ray rich GRB
Hard GRB

Sakamoto 2004
Event rates of XRF/ XRR/ GRB

- February 2001 - September 2003
  - XRF: 15, XRR: 20, GRB: 10
- WXM HV on time
  - 1.1 years
- Field of view of WXM
  - 60° x 60°

XRF: 160 yr⁻¹
XRR: 220 yr⁻¹
GRB: 110 yr⁻¹

BeppoSAX XRFs: ~ 100 yr⁻¹ (Heise et al. 2002)

Underestimation? …. HETE has better sensitivity for detecting XRFs

Event rates of each GRBs

XRF ~ XRR ~ GRB

XRF ~ GRB ~ \( \frac{1}{3} \) All GRBs
The distance of XRFs are close to the Euclidean space.

Sakamoto 2004
Theoretical models of XRFs

Off-axis jet model (Yamazaki et al.)

Unified jet model (Lamb et al.)

Structure jet model (Rossi et al.)

Beamed jet model
Conclusion

- XRFs/XRRs/GRBs form a continuum and are a single phenomenon (broad $E_{\text{peak}}$ distribution).
- “Extended” Amati’s relation will be a key for discussing the prompt emission of GRBs.

Future

We need larger sample of XRFs with the measurement of $E_{\text{peak}}$ and redshifts.

<table>
<thead>
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<th>$E_{\text{peak}}$ of XRF</th>
<th>X-ray detector</th>
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<td>Redshift</td>
<td>Rapid follow-up observation</td>
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The best solution will be…

HETE XRFs $\rightarrow$ Follow-up by Swift