X-Ray Flashes and $E_{\text{iso}} - E_{\text{peak}}$ Relation

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Defining “X-ray flashes” (Heise et al. 2000) as bursts for which \( \log \left( \frac{S_x}{S_{\gamma}} \right) > 0 \) (i.e., > 30 times that for “normal” GRBs)

- \( \frac{1}{3} \) of bursts localized by HETE-2 are XRFs
- \( \frac{1}{3} \) are “X-ray-rich” GRBs

Nature of XRFs is largely unknown

XRFs may provide unique insights into

- Structure of GRB jets
- GRB rate
- Nature of Type Ic supernovae
HETE-2 X-Ray Flashes vs. GRBs

Sakamoto et al. (2004)

GRB Spectrum
Peaks in Gamma - Rays

XRF Spectrum
Peaks in X-Rays
XRF 020903: Discovery of Optical Afterglow

Soderberg et al. (2002)

Palomar 48-inch Schmidt images: 2002 Sep 6 (left image), 2002 Sep 28 (middle image), subtracted image (right image)
XRF 020903: Implications

- HETE-2 and optical follow-up observations of GRB020903 show that in the case of this XRF:
  - It lies on the extensions of the above distributions
  - It lies on an extension of the Amati et al. (2002) relation
  - Its host galaxy is copiously producing stars, similar to those of GRBs
  - Its host galaxy has a redshift $z = 0.25$, similar to those of GRBs

- These results provide evidence that GRBs, X-ray-rich GRBs, and X-Ray Flashes are the same phenomenon
XRF 030723: Optical Afterglow

Fynbo et al. (2004)  
Tominaga et al. (2004)
Density of HETE-2 Bursts in \((S, E_{\text{peak}})-\text{Plane}\)

Sakamoto et al. (2004)
Dependence of GRB Peak Spectral Energy ($E_{\text{peak}}$) on Burst Isotopic Radiated Energy ($E_{\text{iso}}$)

HETE-2 results confirm & extend the Amati et al. (2002) relation:

$$E_{\text{peak}} \sim \{E_{\text{iso}}\}^{0.5}$$

GRB spectra can provide an empirical, predictive redshift estimator that is accurate to a factor of $\sim 1.5$ (Atteia 2003); indicated GRB031026 had $z \sim 14$, but no optical counterpart found.
$E_{\text{gamma}} - E_{\text{peak}}$ Relation

Ghirlanda et al. (2004)
$E_{\text{iso}} - E_{\text{peak}}$ Relation Within BATSE GRBs

Liang & Dai (2004)
HETE-2 results, when combined with earlier results:

- Provide strong evidence that properties of XRFs, X-ray-rich GRBs, and GRBs form a continuum.
- Key result: *approximately equal numbers of bursts per logarithmic interval* in all observed properties.
- Suggest that these three kinds of bursts:
  - Are all the same phenomenon.
  - Are produced by the same central engine.
Observations of XRFs Are Stimulating New Theoretical Ideas

- **XRF & GRB Jet Structure and Burst Rates**

- **XRF—SN Connection**
  - XRFs & GRBs as a Laboratory for the Study of Type Ic SNe ((D. Q. Lamb, T. Q Donaghy & C. Graziani), New Astronomy Reviews, in press (2004)

- **Relativistic Beaming and Off-Axis Viewing Models of XRFs**
Universal Jet vs. Uniform Jet Models

(Diagram from Lloyd-Ronning and Ramirez-Ruiz 2002)
GRBs Have “Standard” Energies

Frail et al. (2001); Kumar and Panaitescu (2001)

Bloom et al. (2003)
$E_{\text{iso}} \propto (\text{theta}_{\text{view}}) \sim E_{\text{gamma}} (\text{theta}_{\text{view}})^{-2}$

- Exponent $= -2$ is necessary to recover the Frail et al. (2001) result (see, e.g., Rossi et al. 2002, Zhang & Meszaros 2002)

- Most viewing angles lie at $\sim \theta_{\text{max}}$ or $\sim 90^0$ to jet axis (whichever is larger) because that is where most of solid angle is

- This implies that most bursts (and most bursts that we see) have large $\theta_{\text{view}}$’s, and therefore small $E_{\text{iso}}$’s, $L_{\text{gamma}}$’s, $E_{\text{peak}}$’s, etc. (Rossi et al. 2002, Zhang & Meszaros 2002, Perna et al. 2003)
Uniform Jet Model

- Frail et al. (2000) result => $E_{\text{iso}} \sim E_{\gamma}/\Omega_{\text{jet}}$
- Amati et al. (2002) relation =>
  \[ E_{\text{peak}} \sim (E_{\text{iso}})^{1/2} \sim (E_{\gamma}/\Omega_{\text{jet}})^{1/2} \]
- HETE-2 results show that $E_{\text{iso}}$ spans ~ 5 decades!
- HETE-2 results imply $N(\Omega_{\text{jet}}) \sim \Omega_{\text{jet}}^{-2}$ =>
  - there are many more bursts w. small $\Omega_{\text{jet}}$'s than large; however, we don't see most of them
  - we see ~ equal numbers of bursts per logarithmic decade in all properties ($\Omega_{\text{jet}}$, $E_{\text{iso}}$, $E_{\text{peak}}$, $L_{\gamma}$, $L_{x}$, $L_{R}$, etc.)!
Simulations of Observed GRBs

- Our approach is the following:
  - We first model the bursts in the source frame
  - We then propagate the bursts from the source frame to the Earth, using the cosmology that we have adopted
  - We determine which bursts are observed, using the properties of the instruments that observe them

- We execute our simulations as follows:
  - For each burst, we obtain a redshift $z$ and a jet opening solid angle $\Omega_{\text{jet}}$ by drawing from specific distributions
  - We introduce three Gaussian smearing functions to generate
    - Spread in jet energy ($E_{\gamma}$)
    - Spread in $E_{\text{peak}}$ around the Amati et al. (2002) relation
    - Spread in the timescale $T$ that converts fluence to flux
  - Using these five quantities, we calculate various rest-frame quantities ($E_{\text{iso}}$, $E_{\text{peak}}$, etc.)
  - Finally, we construct a Band function for each burst and transform it to the observer frame, which allows us to
    - Calculate fluences and peak fluxes
    - Determine if the burst would be detected by various instruments
Gaussian Smearing Functions

- Observed distributions are well-fit by narrow Gaussians
- No evidence for evolution of any of Gaussians w. redshift $z$
Predicted $E_{\text{ios}}$-$E_{\text{peak}}$ Relation

BeppoSAX bursts

HETE-2 bursts
Determining If Bursts are Detected

BeppoSAX bursts

HETE-2 bursts
Comparison of Uniform Jet and Universal Jet Models


Uniform Jet Model

Power-Law Universal Jet Model
Comparison of $\Omega_{\text{jet}}$ ($\Omega_{\text{view}}$) w. Observations

Density of HETE-2 Bursts in $(S, E_{\text{peak}})$-Plane

Sakamoto et al. (2004)
Comparison of Predicted and Observed HETE-2 Fluence and $E_{\text{peak}}$ Distributions

Lamb, Donaghy & Graziani (2003)

Cumulative Distribution ($S_E$)

Cumulative Distribution ($E_p$)

Power-Law Universal Jet Model
Comparison of Predicted and Observed HETE-2 Fluence and $E_{\text{peak}}$ Distributions

Lamb, Donaghy & Graziani (2003)

Uniform Jet Model
$E_{\text{iso}} - E_{\text{peak}}$ Relation

Lloyd-Ronning, Petrosian & Mallozzi (2000); Amati et al. (2002); Lamb et al. (2003)
Comparison of Universal and Uniform Jet Models

- Uniform jet model can account for both XRFs and GRBs
- Power-law universal jet model can account for GRBs, but not both XRFs and GRBs
Comparison of Predicted and Observed $E_{iso}$ and $E_{peak}$ Distributions


Power-Law Universal Jet Model
Comparison of Predicted and Observed $E_{\text{iso}}$ and $E_{\text{peak}}$ Distributions


Uniform Jet Model
Gaussian Universal Jet Model

Zhang et al. (2004)
Implications of the Uniform Jet Model

- Model provides unified picture of XRFs, “X-ray-rich GRBs,” and GRBs
- Extra parameter (distribution of jet opening solid angles $\Omega_{\text{jet}}$) enables it to account for key result: *approximately equal numbers of bursts per logarithmic interval*
- Model implies that $E_{\text{jet}}$ and $E_{\gamma}$ may be $\sim 30$ times smaller than has been thought
- It will be important to determine whether bursts with much smaller values of $E_{\text{iso}}$ and $L_{\text{iso}}$ than the “standard” value are outliers, or are a sign that jet structure is more complicated
- This is particularly true in the case of XRFs, which may have considerably smaller values of $E_{\text{iso}}$ and $L_{\text{iso}}$
Further Implications of Uniform Jet Model

- Model implies most bursts have small $\Omega_{\text{jet}}$ (these bursts are the hardest and most luminous bursts); however, we see very few of these bursts.

- Range in $E_{\text{iso}}$ of five decades $\Rightarrow$ minimum range for $\Delta\Omega_{\text{jet}}$ is $6 \times 10^{-4} < \Omega_{\text{jet}} < 6$.

- Unified jet model therefore implies that there are $\sim 10^5$ more bursts with small $\Omega_{\text{jet}}$'s for every such burst we see $\Rightarrow$ if so, $R_{\text{GRB}}$ may be comparable to $R_{\text{SN}}$.

- However, efficiency in conversion of $E_{\gamma}$ ($E_{\text{jet}}$) to $E_{\text{iso}}$ may be less for XRFs.
X-Ray and Optical Afterglows of XRFs Are Also Faint

Lamb, Donaghy & Graziani (2003)
HETE-2 Bursts in \((S, E_{\text{peak}})\)-Plane

Sakamoto et al. (2004)
X-Ray Flashes vs. GRBs: HETE-2 and Swift (BAT)

Even with the BAT’s huge effective area (~2600 cm²), only HETE-2 can determine the spectral properties of the most extreme half of XRFs.
Ability of HETE-2 and Swift to Measure $E_{\text{peak}}$ and $S_{\text{bol}}$ of XRFs

$E_{\text{peak}}(\text{est})$ vs. $E_{\text{peak}}(\text{actual})$:
- Shaded areas are 68% confidence regions
- Swift (red): undetermined for $E_{\text{peak}} < 20$ keV
- HETE-2 (blue): well-determined down to $E_{\text{peak}} \sim 3$ keV
- Data points are actual HETE XRF measurements

$S_{\text{bol}}(\text{est})$ vs $S_{\text{bol}}(\text{actual})$:
- Shaded areas are 68% confidence regions
- Swift (red):
  - well-determined for $E_{\text{peak}} > 20$ keV
  - only lower limit for $7$ keV $< E_{\text{peak}} < 18$ keV
  - undetermined for $E_{\text{peak}} < 7$ keV
- HETE-2 (blue): well-determined down to $E_{\text{peak}} \sim 3$ keV
Conclusions

- HETE-2 has provided strong evidence that XRFs, “X-ray-rich” GRBs, and GRBs are all the same phenomenon.
- XRFs provide unique insights into:
  - structure of GRB jets
  - GRB rate
  - nature of Type Ic SNe
- Uniform jet model can provide unified picture of all three kinds of bursts, whereas universal jet model cannot.
- Confirmation will require:
  - localization of many XRFs
  - determination of $E_{\text{peak}}$
  - identification of optical afterglows
  - determination of redshifts
- HETE-2 is ideally suited to do the first two, whereas Swift (with $E_{\text{min}} \sim 15$ keV) is not; Swift is ideally suited to do the second two.
- Therefore, scientific partnership between HETE-2 and Swift will greatly advance our understanding of XRFs.