Towards a More Standardized Candle Using GRB Energetics and Spectra

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Outline

- GRB Cosmography: Motivations
- GRB Standard Candles: Energetics
- The Ep-Eγ Relation: Current Status
- Future Prospects
Motivations

Despite numerous attempts to estimate the cosmological closure parameter, $\Omega$, its actual value is still unknown, and current estimates range from 0.2 to 1 (see, e.g., Peebles 1996). One may wonder whether GRBs would provide a meaningful independent estimate of $\Omega$. Using GRB peak-flux statistics alone, $\Omega$ could not be estimated from the current data (Cohen & Piran 1995). However, given a cosmological distribution of sources with measured redshifts, we can try to estimate $\Omega$ in a manner similar to the attempts to estimate $\Omega$ from Type I supernovae by Perlmutter et al. (1996). Perhaps GRBs will not be able to contribute meaningfully to the myriad of measurements before other methods become more precise, but it is likely that they provide a useful consistency check based on independent objects. Recall that GRBs are most likely farther than the observed Type I supernovae.

Cohen & Piran 1997

Also see Dermer 1992, Rutledge et. al 1995
Motivations

- GRBs: brightest explosions in universe
- Detectable out to high $z > 2$ (easy); both prompt-emission and afterglow ($z_{\text{max}} \sim 10-20$)
- Gamma-rays penetrate dust
- More tractable $k$-corrections
- Any evolution orthogonal to Type Ia SNe
- *Swift* in space! vs. *SNAP* >2010? ($z_{\text{max}} \sim 1.7$)

A GRB standard candle could serve as an independent probe of the geometry & expansion history of the universe, complementary to SNe Ia
Motivations

- But high $z > 1.7$ is $\Omega_M$-dominated; only low $z$ regime is good for dark energy, e.g. $\Omega_\Lambda$, $w$, right?
- Few nearby GRBs in current sample; only 3 $w/\ z < 0.2$, including peculiar bursts 980425, 031203.
- However, survey in full range $0 < z < 2+$ is crucial to pin down systematics for dark energy, $w(t)$, $z_T$ ([Linder & Huterer 2003] ($z_{\text{max}} \sim 1.7$ now, SNAP))
- Furthermore, GRBs in $1 < z < 2$ already comparable in number to high-$z$ SNe Ia from HST ([Riess et. al 2004]), clearly an interesting region for dark energy

GRBs + SNe Ia: independent objects, techniques, different systematics 😊
GRB Standard Candles?

What function of observables might serve as a useful GRB standard candle? Purely empirical approach.

- It must be roughly constant from burst to burst – or at least come from a narrow intrinsic distribution
- It must not evolve (or evolve weakly) with redshift
- It can depend on properties of both the prompt emission and the afterglow, although the latter are more observationally expensive
- Search for a standard candle, some function of GRB observables in the set of ∼40 bursts with known z
- Focus on energetics, although others proposed
**Isotropic Equivalent Energy (E_{iso})**

- **E_{iso} distribution** – spans several orders of mag. – **E_{iso} is a bad standard candle**

![Histogram of E_{iso} with known redshifts](image)

**Formula for E_{iso}**

\[ E_{iso} = \frac{4\pi S_\gamma k DL_{th}^2 h_{70}^{-2}}{1 + z} \]

- **N**
- **Bin = 0.5**
- **39 GRBs with Known Redshift**
- **Fluence in observed bandpass**
- **Cosmological k-correction**
- **Luminosity Distance (theory)**
- **Hubble constant /70 kms\(^{-1}\)Mpc\(^{-1}\)**
- **Redshift**

GRB Jets & Beaming

- Beaming fraction $f_b$ inferred from achromatic break in afterglow light curve ($t \sim t_{\text{jet}}$)

$$E_\gamma = E_{\text{iso}} f_b$$

"Top Hat" Jet Model

$$f_b = 1 - \cos(\theta_{\text{jet}})$$

- $\theta_{\text{jet}} = 0.101 \text{ rad} \left( \frac{t_{\text{jet}}}{1 \text{ day}} \right)^{3/8} \left( \frac{\eta_\gamma}{0.2} \right)^{1/8} \left( \frac{n}{10 \text{ cm}^{-3}} \right)^{1/8}$$

$$\times \left( \frac{1 + z}{2} \right)^{-3/8} \left( \frac{E_{\text{iso}}}{10^{53} \text{ erg}} \right)^{-1/8}$$

Stanek et. al 1999
Determining $E_\gamma$

To determine $E_\gamma$ one needs to assume a cosmology, pick a model for the jet structure, and “measure” the following:

1. Fluence in observed bandpass ($S_\gamma$) \textbf{VERY EASY}
2. Peak of prompt-burst spectrum ($E_p$) \textbf{EASY}
3. Spectroscopic redshift ($z$) \textbf{HARD}
4. Time of afterglow jet-break ($t_{jet}$) \textbf{HARD}
5. Ambient Density ($n=10$ cm$^{-3}$ ?) \textbf{VERY HARD}
6. $\gamma$-ray conversion efficiency ($\eta_\gamma=20\%$) \textbf{UNKNOWN}
Beaming Corrected Energy ($E_\gamma$)

- With assumptions for $n$, $\eta_\gamma$, $E_\gamma$ distribution is much narrower than $E_{iso}$ (Frail et. al 2001, Piran et. al 2001, Bloom et. al 2003). This became the “Frail Relation”: $E_\gamma \sim$ constant

\[ E_\gamma = E_{iso} f_b \]

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15 GRBs (f$_b$), 17 GRBs (z) 
Frail et. al 2001

24 GRBs (f$_b$), 29 GRBs (z) 
Bloom et. al 2003
Without a low-z calibration set, must re-fit for standard candle Energy - new Hubble diagram for each cosmology

But scatter similar for each cosmology. Not much topology in $\chi^2$ surface.

GRB standard candles from $E\gamma$ promising but not sufficient for cosmography

Bloom, Frail, Kulkarni 2003
E_γ is getting **worse** new data: e.g. 030329, 031203, X-Ray Flash (XRF) 020903, 030723

GRB 980425 (z=0.0085 /SN1998bw) is not a singular anomaly in prompt energy release

**Frail et. al 2001**  **Bloom et. al 2003**  **Ghirlanda et. al 2004**
Updated Comparison: $E_\gamma$ vs. $E_{iso}$

Data from Friedman & Bloom 2005 (astro-ph/0408413)
Can Different Jets Save $E_\gamma$?

- Alternative Jet Models (Structured Jets – Not Top Hats):
  * Power Law: Rossi et. al 02, Zhang & Meszaros 2002

- Perhaps the low $E_\gamma$ GRBs are viewed off-axis?
- Structured jets w/ more energy on-axis find natural support in numerical simulations of collapsar model: (MacFadyen et. al 1999, 2001)
- But alternative jet models come at expense of new, unknown free parameters, which may vary between GRBs
- Even these can not recover standard $E_\gamma$ for 030329, XRFs
- Give up? Or combine with other correlations?
GRB Spectra: “Band Model”

- Simple, smooth broken power Law (Band et. al 1993)
- Low energy index \((1+\alpha)\): \(\nu F\nu\) spectrum
- High energy index \((1+\beta)\): \(\nu F\nu\) spectrum
- Peak energy of \(\nu F\nu\) spectrum: \((E_p)\)
- Band Spectrum describes most bright BATSE GRBs

4/12 GRB Spectra w/ z

Amati et. al 2002

(Preece et. al 2000)
The $E_p - E_{iso}$ "Amati" Relation

Amati et. al 2002
12 GRBs w/ z

Lamb et. al 2004
Extends to XRFs

Much discussed correlation: $E_p \sim (E_{iso})^{1/2}$
The $E_p-E_\gamma$ “Ghirlanda” relation

- $E_p \sim (E_\gamma)^{2/3}$
- Smaller scatter than Amati relation.
- Based on more physical geometry-corrected energy
- New standard candle contender?
- **But we must remember the pitfalls with $E_\gamma$, which depends on the cosmology.**

Ghirlanda et al. 2004a
Dai et. al use $E_p - E_\gamma$ relation to construct a GRB standard candle, test cosmological models

- Present strong constraints: $\Omega_M = 0.35 \pm 0.15 \ (1-\sigma)$, assuming flatness
- Also try to constrain $\omega$ with GRBs alone

However, Dai et. al assumed $\eta = 2/3$ for all cosmologies...
Present joint fit w/ SNe Ia, claim GRBs + SNe Ia more consistent with WMAP

Some improvements: re-fit $\eta$ in each cosmo.

But it was not possible to reproduce their results from their papers alone

- Few equations
- Assumptions unclear
- $\chi^2$/dof not reported for $E_p$-$E_\gamma$ relation

Ghirlanda et. al 2004b
The $E_p$-$E_\gamma$ relation

Inset: cosmology dependence of $\eta$

$$E_p = \kappa \left( \frac{E_\gamma}{E^*} \right)^\eta$$

$\chi^2$/dof = 3.71 (17 dof)

Poor fit to a power law, at least under the assumptions we made...

Friedman & Bloom 2005
Controversy

- At “GRBs in the Afterglow Era: 4th Workshop”, Rome Italy, Oct 18-22, 2004, Ghirlanda et. al report at good fit ($\chi^2_v = \chi^2/dof = 1.27; 13 \text{ dof}$) to the $E_p-E_\gamma$ relation

- Can we reconcile this with our poor fit? ($\chi^2_v = 3.71; 17 \text{ dof}$), by comparing assumptions, data sets?
Sensitivity to Input Assumptions

\( \chi^2_v = 3.71 \): upper left, red triangle (Friedman & Bloom, 2005)
\( \chi^2_v = 1.27 \): lower right, green diamond (Ghirlanda et. al 2004c)

Goodness of fit sensitive to:

1. Density \((n)\)
2. Fractional error \((\sigma_n/n)\)
3. Data set, references for individual bursts (small # statistics)

\( \chi^2_v \) vs. \( n, \sigma_n/n \) for different data sets and assumptions.

- Set A: [20,20000] keV
- Set G: [20,20000] keV
- Set A: [1,100000] keV
- Set G: [1,100000] keV

Choices of \( n, \sigma_n/n \):
- This paper
- Ghirlanda et. al 04a,b
- Dai et. al 04
- Bloom et. al 03
- Frail et. al 01*

Friedman & Bloom 2005
Sensitivity to Input Assumptions

An acceptable fit for the cosmology requires an acceptable fit for the $E_p - E_\gamma$ relation which is *highly sensitive to assumptions*

- All nominal outliers – except 980425, 031203, 990510* can be made to fall on relation simply by changing density (efficiency), errors
  
  \[ E_\gamma \propto [(n/10 \text{ cm}^{-3})(\eta_\gamma/0.2)]^{1/4} \]

- There exist assumptions, data subsets that yield good fits, (e.g. Dai et. al, Ghirlanda et. al), but these are not necessarily favored *a priori*

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*Friedman & Bloom 2005*
For self-consistency, one must re-fit for the slope ($\eta$) and intercept ($\kappa$) of the $E_p$-$E_\gamma$ relation in each cosmology.

**Apparent GRB Luminosity Distance** [cm]

$$Dl_\gamma \propto (E^*)^{2/3} \left( \frac{E_p}{\kappa} \right)^{2/3\eta}$$

(Small angle approx.)

**Apparent GRB Distance Modulus** [mag]

$$DM_\gamma \approx -2.5 \log \left( \frac{4\pi S_\gamma kt_{jet} (n\eta_\gamma)^{1/3}}{(1 + z)^2} \right) + C_\gamma + zp$$

**Empirical Correction From $E_p$-$E_\gamma$ relation** [mag]

$$C_\gamma = \frac{10}{3\eta} \log \left( \frac{E_p^{obs}(1 + z)}{\kappa} \right)$$

$$zp = \frac{10}{3} \log \left( \frac{2E^*}{B^2} \right) - 5 \log(3.085 \times 10^{19} \text{ cm}) + 5 \log(h_{70})$$
Improvement

- Goodness of fit \( (\chi^2_v) \) for DM-z relation computed as in upper left panel for each cosmology in grid.
- \( (\chi^2_v)_{\text{min}} \) gives favored \( (\Omega_M, \Omega_\Lambda) \) cosmology.
- But \( \chi^2_v \sim 6 \) for standard cosmology under our assumptions

So is \( \chi^2_v \) acceptable for any \( (\Omega_M, \Omega_\Lambda) \) cosmology?
Goodness of fit ($\chi^2_v$) for DM-z relation computed for each cosmology in grid.

$\chi^2_v$ gives favored cosmology $(\Omega_M, \Omega_\Lambda)$. Favored loitering cosmology $(\Omega_M, \Omega_\Lambda) = (0.12, 1.32) \rightarrow$ almost no Big Bang

But $\chi^2_v$ > 2 for a range of assumptions for $n$, $\sigma_n/n$; (poor fit)

Friedman & Bloom 2005
GRBs: Not Ready For Cosmography

- Sensitivity to input assumptions
- Small number statistics
- Few low-z bursts ($\Omega_{\Lambda},w$)
- Lack of low “training set” to calibrate relation ($\eta$), in a cosmology-independent way
- Contours in Hubble diagram not meaningful

- Current data do not rule out that the relation will be well fit by a power law, but still, one must be cautious regarding current claims of the utility of GRBs for cosmography
Differences stem from input assumptions, data selection, and method of analysis

Dai et. al exclude the two largest outliers: 990510, 030226 (+ 970508 + 3 other bursts)

Assumed $n=3$ cm$^{-3}$, greatly improving the fit compared to our assumption ($n=10$ cm$^{-3}$)

Assumed slope of relation fixed ($\eta=2/3$) for all cosmologies. This slope was fit assuming the WMAP cosmology. Circularity problem.
Improvements from Dai. et. al 2004
- Self-consistent re-calibration of relation ($\eta$) for each cosmology
- Stressed need for low-z calibration bursts

Ghirlanda et. al fit to $E_p - E_\gamma$ relation ($\chi^2=1.27$) compared to our ($\chi^2=3.71$), highlights extreme sensitivity to input assumptions, data selection

Assumptions not made clear in their paper

Not possible to reproduce their results without further investigation (conference + conversations)

Investigation elucidated sensitivity to assumptions
Present joint fit w/ SNe Ia, claim GRBs + SNe Ia more consistent with WMAP

Fit dominated by 156 SNe

Ignores fact that GRBs alone are almost inconsistent w/ Big Bang (i.e. loitering cosmology)

Bad GRB data pulls SNe Ia data in a “favorable” direction

Assuming flatness is fine, but what if SNe Ia, LSS, & CMB didn’t exist?

Must rigorously test GRBs alone before combining with SNe Ia
1. Low redshift calibration (possible w/ *Swift*)
   - 3/39 GRBs detected w/ $z < 0.2$
   - 030329: large outlier in $E\gamma$ but falls directly on $E_p-E\gamma$ relation – low-$z$ anchor of the relation
   - However, 2 lowest $z$ GRBs (980425, 031203) are outliers independent of density assumptions

2. Could know slope ($\eta$) of relation *a priori* from physics, obviating need to re-fit in every cosmology.
   - Physical basis is not understood: Eichler & Levinson 2004, Rees & Meszaros 2004
   - Selection effects – Band & Preece 2005
   - On much less stable footing than SNe Ia mag corrections
- Cosmological k-correction bandpass choice
- Neglecting Covariance
- Gravitational Lensing
- WIND vs. ISM
- Assuming the *same* density for all bursts
- Assuming the *same* efficiency for all bursts
If with refinements to relation, expanded data set, GRBs prove to be standardizable candles:

- Test cosmology to $z > 10$ ($z_{\text{max}} \sim 1.7$ for SNe Ia)
- Determine $\Omega_M$ to higher precision
- Determine transition $z_T$ to epoch of deceleration
- Help pin down dark energy systematics, $w(t)$
- + No dust/reddening, simple k-corrections, several years before SNAP launches (> 2010?)
If correlation is upheld by future data, one can assume a cosmology and learn about GRBs

- Physical basis of correlation may lend insight into GRB radiation mechanisms, jet models

- Outliers to the relation may indicate separate sub-classes of GRBs that may come from different progenitor systems (e.g. 980425, 031203), or at least tell us about GRB diversity

- Follow up observations of independent interest
Final Thoughts

It’s difficult to do science when you already know the “right” answer

\[(\Omega_M, \Omega_\Lambda, h) = (0.27, 0.73, 0.71)\]

Independent techniques in science are only good when they’re independent.
Conclusions

- The cosmographic utility of a GRB standard candle constructed from the $Ep-E_\gamma$ relation is highly sensitive to input assumptions, data selection (+ systematics & selection effects)

- Need better constraints on the density (efficiency) from early-time afterglow follow up, broadband afterglow modeling

- Need more data from Swift to combat small # statistics (only ~20 bursts on $Ep-E_\gamma$ relation, ~40 with measured z)

- This work strengthens the science case for the continued symbiosis of HETE II (30-400 keV) spectral range vs. (15-150) Swift for all Applications of the $Ep-E_\gamma$ relation

Cosmography with GRBs is still possible, but is not yet competitive with Type Ia SNe
References


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GRB Redshift Indicators

- Previous GRB redshift indicators used prompt $\gamma$-ray properties alone, using correlations found between isotropic luminosity ($L_\text{iso}$) and

- **Variability:** Fenimore & Ramirez Ruiz 2000, Reichardt et. al 2001, Lloyd-Ronning & Ramirez-Ruiz

- **Spectral Lags:** Norris et. al 2000, Noriss 2002, Schaefer et. al 2001

- Renewed enthusiasm for cosmographic utility of GRBs: Schaefer 2003, Takahashi 2003

- Focus on those derived from *energetics*
Motivations

- GRBs: brightest explosions in universe
- Detectable out to high $z > 5$ (easy), $z_{\text{max}} \sim 10-20$ (?)
- Gamma-rays penetrate dust / cleaner k-corrections
- Any evolution likely orthogonal to Type Ia SNe
- *Swift* satellite in space! $SNAP > 2010?$ ($z_{\text{max}} \sim 1.7$)

A GRB standard candle could serve as an independent probe of the geometry & expansion history of the universe, complementary to SNe Ia
Turning the game around - *Pick a cosmology* - GRB standard candles can tell you about the progenitors of GRBs

- Scatter about standard candle can help quantify burst diversity (e.g. peculiar Ia’s)
- Empirical corrections can yield new insight into underlying physics (e.g. peak brightness–decline rate: Ia’s, $^{56}$Ni variation)
- Large deviations from the standard candle (outliers) may indicate different physical mechanisms for making GRBs – i.e. different progenitor systems (e.g. Type II SNe)
Cosmology Dependence

\[ \eta = 0.669 \pm 0.034 \]

\[ (\Omega_M, \Omega_\Lambda, h) = (0.3, 0.7, 0.70) \]

- Slope does not vary dramatically between cosmologies
- However, it must be re-fit in each one for self-consistent cosmography

Friedman & Bloom 2005
Sensitivity to Input Assumptions

 Choices of \( n \) (\( \sigma_n/n \))
- \( \bullet \) this paper
- \( \Delta \) Ghirlanda et. al 04a,b
- \( \bigstar \) Dai et. al 04
- \( \Box \) Bloom et. al 03
- \( \bigcirc \) Frail et. al 01*

 Set A [20,2000] keV

 Set G [20,2000] keV

 Data From Ghirlanda et. al 04a

 Set A [1,10000] keV

 Set G [1,10000] keV

 Set G* [1,10000] keV

\[
\chi^2_{\nu,\text{min}} \quad [n_{\text{min}}]
\]

\[
\begin{array}{c|c|c|c|c|c|c}
\hline
\, & \chi^2_{\nu,\text{min}} \quad [n_{\text{min}}] & \hline
\, & \hline
3.39 \quad [1.46] & \hline
3.06 \quad [1.51] & \hline
2.21 \quad [1.60] & \hline
1.34 \quad [1.61] & \hline
\, & \hline
\, & \hline
\end{array}
\]
Gamma-Ray Bursts: Cosmological?

2704 BATSE Gamma-Ray Bursts

- Isotropy → Strong Evidence For Cosmological Origin
Bimodal Duration Distribution

(Kouveliotou et. al 1993) http://www.batse.msfc.nasa.gov/batse/grb/duration/

- Short Duration GRBs: $T_{90} < 2s$ (~25%)
- Long Duration GRBs: $T_{90} > 2s - 1000s$ (~75%)
- Bimodal Dist. → 2 Distinct Progenitor Subclasses
Afterglow Era: 1997 - present

- **BeppoSax**: X-Ray Afterglow for GRB 970228 detected (Costa et. al 1997)

- Optical Follow-Up (van Paradijs et. al 1997, Frail et. al 1997)

- GRB 970508, first red-shift detection ($z = 0.835$) (Metzger et. al 1997)

- GRB 970508 Host Galaxy Identification (Bloom et. al 1998)

- Case for cosmological origin of at least some long GRBs is sealed
Fireball Model

Rees & Meszaros, 1992, 1994

- Generic even without knowledge of “central engine”
Energy Budget

$E\sim 10^{51}-10^{54}$ erg

- **Internal Shocks** - Prompt $\gamma$-rays (GRB)
- **External Shocks** - Afterglow: X-ray, Optical, Radio
Offset distribution from host galaxy center does not fit predicted distrib. for binary merger (e.g. NS-NS) models.

Fits offset distribution associated with star forming regions \(\rightarrow\) favors massive star progenitors for long GRBs.

Bloom et. al 2002
GRB-Supernova Connection

- GRB 980425/SN 1998bw ($E_{iso} \sim 10^{47}-10^{48}$ erg)
- GRB 980326: Late Bump in Light Curve (Bloom et. al 1999) – Also some evidence for bumps in ~10 other GRBs (Bloom et. al 2003, IAU Colloquium)
- GRB 030329/SN 2003dh – First Spectroscopic Confirmation (Stanek et. al 2003)
- 021211 /SN 2002lt (della Valle et. al 2004)
- GRB 031203 /SN 2003lw
Collapsar Model

- Core Collapse Type Ib/c SNe - Massive (~20-40M☉)
- Wolf-Rayet Star (H, He envelope lost) → BH
- Stellar Material Forms Accretion Disk Around Rapidly Rotating BH
- Accretion Lifetime ~ Duration of GRB (~1-10³s)
- Relativistic Jets (How?)
- Potential Energy From Disk Mass + BH Spin (B-Z)
  - E~10⁵¹-10⁵⁴erg

McFadyen, Woosley, & Heger 2001
GRB “Animator’s Rendition”

Images\GRBstar2.mov
One may wonder whether perhaps GRBs would provide a meaningful independent estimate of $\Omega$ ... Perhaps GRBs will not be able to contribute meaningfully to the myriad of measurements before other methods become more precise, but it is likely that they provide a useful consistency check based on independent objects.

Cohen & Piran, 1997
Improvement

Major reduction in scatter from $E_{\text{iso}}$, $E_{\gamma}$ as GRB “standard candles”
Goodness of fit ($\chi^2$/dof) for distance modulus-relation computed for each cosmology in grid. 

$(\chi^2$/dof)$_{\text{min}}$ gives favored $(\Omega_M, \Omega_\Lambda)$ cosmology.

But $\chi^2$/dof > 3 under our assumptions

So is $\chi^2$/dof acceptable for any $(\Omega_M, \Omega_\Lambda)$?