Gamma-Ray Bursts as Tracers of High-Redshift Star Formation: Promises and Perils

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ArXiv:1301.5903
(+ abundant wild speculation)
Cosmic Star-Formation History

Behroozi et al. 2011
Cosmic Star-Formation Sites

Redshift

Cosmic star formation history (ULIRGs)

Total SFR
ULIRG SFR

Smolcic et al. 2008

Santini et al. 2009

1.5 < z < 2

Stellar Mass (M_☉)

SFRD / d(log(M_☉))
High-z SF History from GRBs

Burst luminosity $L_{iso}$ [erg s$^{-1}$]

$10^{49}$ $10^{50}$ $10^{51}$ $10^{52}$ $10^{53}$

$z$ 0 1 2 3 4 5 6 7

Absorption
Emission
Photometric

Kistler et al. 2008

Starling + 2005

Galaxies & GRBs @ Cabo del Gata
GRBs as Tracers of Cosmic Star Formation

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Advantages of GRB Selection

Inexpensive
Optical afterglow redshifts are “cheap”
(1 hr on a 4m telescope typically adequate)

Dust-Unbiased, in principle
Gamma-ray burst and X-ray/radio
afterglows unimpeded by dust

Sensitive to sub-threshold SFR
Host nondetections give a direct constraint
on importance of undetectable galaxies

Extendable to $z>8$ and potentially higher

No Cosmic Variance
GRB satellites see (close to) the whole sky

$M_{F606W} = 27$
$M_B = -17.2$

$M_{F110W} > 30$
$M_{UV} > -17.5$

Tanvir et al. 2010

$z=0.937$

$z=8.2$

Tanvir et al. 2012
High-z SF History from GRBs

Behroozi et al. 2011

Cosmic SFR \([M_\odot \text{yr}^{-1} \text{Mpc}^{-3}]\)

HB06
Fit (HB06)
Fit (New)
UV
UV+IR
H\alpha
IR/FIR
1.4 GHz
High-z SF History from GRBs

Cosmic SFR [M_☉ yr⁻¹ Mpc⁻³]

0.1

0.01

0

2

4

6

8

z

Behroozi et al. 2011

Kistler et al. 2008

Robertson & Ellis 2011

GRBs
High-z SF History from GRBs

Peaks at z~3, not z~2

Successful high-z GRB detections imply large z>5 SFRD
Interpretations

- GRB and field-survey measurements of the SFRD do not agree. Why not?

1. Field surveys systematically underestimate (by factor of ~5!) contributions from low-mass galaxies and high-z galaxies.
   e.g., Jakobsson et al. 2012, Kistler et al. 2013

2. GRBs are not uniform star-formation rate tracers: the rate depends on environment (e.g., metallicity)
   e.g., Modjaz et al. 2008, Levesque et al. 2010, Graham & Fruchter 2012
Dramatic Metallicity Bias at z~0.5

Graham & Fruchter 2012
Dramatic Metallicity Bias at z~0.5

Graham & Fruchter 2012

Galaxies & GRBs @ Cabo del Gata

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GRBs as Tracers of Cosmic Star Formation

Dramatic Metallicity Bias at z~0.5

Graham & Fruchter 2012

b/l Ic's
Dramatic Metallicity Bias at \( z \sim 0.5 \)

- Long-duration Gamma Ray Burst (LGRB)
- Broad-lined Type Ic SNe (w/ no GRB)
- Targeted \( \bullet \) Untargeted \( \bigcirc \) Survey
- TKRS galaxies (from KK04)
- SDSS galaxies (small points)
- \( \text{SN 1997ef} \)
- \( \text{SN 1997dq} \)
- \( \text{SN 1998ey} \)
- \( \text{SN 2002bl} \)
- \( \text{SN 2003bg} \)
- \( \text{SN 2005ks} \)
- \( \text{SN 2006aj} \)
- \( \text{SN 2007ce} \)
- \( \text{SN 2008iu} \)
- \( \text{SN 2010ah} \)
- \( \text{GRB 050824} \)
- \( \text{GRB 060103} \)
- \( \text{GRB 070612} \)

\text{GRBs}

b/l Ic's

Graham & Fruchter 2012

Galaxy Absolute Magnitude (\( M_B \))

Oxygen Abundance \([12+\log(O/H)]\)
At high redshift (where most GRBs occur), all galaxies are metal “poor”.

Direct metallicity measurement not usually practical (except for extremely luminous hosts)
Hosts at $z > 1$

Savaglio et al. 2009

(also, Castro Ceron et al. 2010)
Hosts at $z>1$

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Galaxies & GRBs @ Cabo del Gata

GRBs as Tracers of Cosmic Star Formation

where are the massive GRB hosts?

Savaglio et al. 2009

(also, Castro Ceron et al. 2010)
~25% of GRBs are **dark**:

- No optical afterglow, even with early follow-up.

- Can't identify host without X-ray or radio follow-up.

- Can't measure redshift without large ground-based telescopes.

Most are **dust-obscured**

- Perley et al. 2009, Greiner et al. 2011

These hosts were *not routinely followed* in previous work: bias?
Swift's **XRT** (positional accuracy ~1.5") lets us locate these bursts and find their hosts. (At least one of: Chandra, radio, and/or fast NIR follow-up usually also available to confirm position / host ID)
Some Dark GRB Hosts

GRB 080207
- Svensson et al. 2012
- Hunt et al. 2011

GRB 080607
- Chen et al. 2011

GRB 080325
- Hashimoto et al. 2011

GRB 051022
- Castro-Tirado et al. 2007
- Rol et al. 2007

GRB 020819
- Levesque et al. 2010

GRB 070306
- Jaunsen et al. 2008

GRBs 070802, 080605, 080805, 081109, 090926B, 100621A
- Krühler et al. 2011
- Rossi et al. 2012

Gravitational Wave Transients 2019
Sample Selection

Quasi-complete sample of all GRBs from 2005-2009 with evidence of $A_V > 1$ mag (from afterglow color/SED)
Optical Host Mosaic
Spitzer Host Mosaic

- Xray position
- Optical/IR/mm/radio position
- Host galaxy position
Redshift Measurement

Lyman-break photo-z

Lyman alpha emission

IR spectroscopy

Balmer-break photo-z

Specific flux \( F_{\nu} \) (erg/s/cm\(^2\))

Wavelength (\( \mu m \))

Specific flux \( F_{\nu} \) (erg/s/cm\(^2\))

IR spectroscopy

Kruhler et al. 2012
Redshift Measurement

- Lyman break phot-z
- Balmer-break phot-z
- IR spectroscopy
- Lyman alpha emission
- All Swift GRBs
- Dusty GRBs
- Kruehler et al. 2012

GRBs as Tracers of Cosmic Star Formation
SED Fitting

Specific flux $f_\nu$ (erg cm$^{-2}$ s$^{-1}$)

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>Specific flux $f_\nu$ (erg cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>1</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>4</td>
<td>$10^{-16}$</td>
</tr>
</tbody>
</table>

Galaxies & GRBs @ Cabo del Gata

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GRBs as Tracers of Cosmic Star Formation
SED Fitting

Fitting conducted with custom code using Bruzual & Charlot 2003 libraries, Calzetti extinction, Chabrier IMF, constant SF history with impulsive change allowed at 10 Myr
Pre-Swift events only:

Blue = unobscured GRB,  Red = obscured GRB.

- Stellar Mass
- SFR
- Extinction
Comparisons at $z \sim 1$

Samples overlap considerably...

Combined pre-Swift + dark sample:

- Blue = unobscured GRB
- Red = obscured GRB

- **Stellar Mass**
- **SFR**
- **Extinction**

Graphs showing data points for stellar mass, SFR, and extinction as a function of redshift. The red and blue markers indicate obscured and unobscured GRBs, respectively.
But on average, obscured hosts are more massive, star-forming, and dusty.

Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.

- **Stellar Mass**
  - Dark median
  - Unobscured median

- **SFR**
  - Dark median

- **Extinction**
  - Mean extinction ($A_V$)

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This produces modest changes in the population averages.

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Combined pre-Swift + dark sample:

Blue = unobscured GRB, Red = obscured GRB.
Comparisons vs. Field Galaxies at z~1

Looks “consistent” with field galaxy number distributions...

Grey points: field galaxies from MOIRCS deep survey (Kajisawa et al. 2011), omitting AGN (hard X-ray detection).

Combined sample versus field galaxies:

Stellar Mass

SFR

Extinction
Weighting by SFR is essential. Null hypothesis is $R_{GRB} \propto SFR$.

Grey points: field galaxies from MOIRCS deep survey (Kajisawa et al. 2011), omitting AGN (hard X-ray detection). Point size scaled by UV+IR SFR.

Combined sample versus field galaxies:
Comparisons vs. Field Galaxies at z~1

Calculate z-dependent median (mass, SFR, Av) of SFR-weighted population. Half of GRBs should be above median, half below (if $R_{GRB} \propto SFR$)

Combined sample versus field galaxies:

- Stellar Mass
- SFR
- Extinction

Half of GRBs should be above median, half below.
Comparisons vs. Field Galaxies at $z \sim 1$

Calculate $z$-dependent median (mass, SFR, $A_v$) of SFR-weighted population. Half of GRBs should be above median, half below (if $R_{GRB} \propto SFR$)

Combined sample versus field galaxies:

- **Stellar Mass**
- **SFR**
- **Extinction**

- 50% of GRBs?
- 50% of GRBs?
- 50% of GRBs?
Half of GRBs should be above median, half below (if $R_{GRB} \propto SFR$)

### Stellar Mass
- 7 GRBs
- 50% of SF
- 50% of SF
- 19 GRBs

### SFR
- 11 GRBs
- 50% of SF
- 50% of SF
- 15 GRBs

### Extinction
- 7 GRBs
- 50% of SF
- 50% of SF
- 20 GRBs
For more resolution, use quartiles:

**Stellar Mass**
- 2 GRBs (25% of SF)
- 13 GRBs

**SFR**
- 7 GRBs (25% of SF)
- 8 GRBs

**Mean extinction ($A_v$)**
- 3 GRBs (25% of SF)
- 9 GRBs
GRBs are poor tracers of star-formation at $z \sim 1$, even when dark GRBs are included.
GRBs are poor tracers of star-formation at $z \sim 1$, even when dark GRBs are included.

Not too surprising... but what about $z \sim 2$?

GRBs vs SFR at z~2

HST IR Snapshot program

45 randomly selected optically-bright Swift GRBs (known z<3) observed to limit of $H \sim 25$ AB mag

Tibbets-Harlow et al. in prep

VLT Optically Unbiased Host Project (“TOUGH”)  

69 uniformly selected Swift GRBs observed to limits of $R \sim 27$ AB mag and $K \sim 23$ AB mag

Hjorth et al. 2012  
Malesani et al. in prep.  
Jakobsson et al. 2012
Use magnitudes and colors as substitutes for formal SED modeling.

Dark + pre-Swift + Snapshot + VLT

- **H-band magnitude** (mass proxy)
- **R-K color** (age+dust proxy)

Use magnitudes and colors as substitutes for formal SED modeling.
GRBs vs SFR at $z \sim 1$

Divide by star-formation quartiles, repeating analysis at $z \sim 1$ first:

- **H-band magnitude** (mass proxy)
- **R-K color** (age+dust proxy)

$z=0.5-1.4$

**Graphs:**
- **Left:** H-band magnitude vs redshift for different star-formation quartiles.
- **Right:** R-K color vs redshift for different star-formation quartiles.

**Legend:**
- 0
- 30
- 23

**Axes:**
- **X-axis:** Redshift
- **Y-axis:** Apparent F160W magnitude (AB) for H-band, R-K color (Vega) for R-K color

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GRBs vs SFR at z~2

Divide by star-formation quartiles at z~2. Trend still present (but less pronounced).

H-band magnitude (mass proxy)

R-K color (age+dust proxy)

z=1.5-2.5
GRBs are biased SFR tracers until at least $z \sim 2$. 
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GAME OVER
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**GAME OVER**
• GRBs are biased SFR tracers until at least $z \sim 2$. 
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![Graph showing metallicities and masses for different redshifts](image)
The number of GRBs per unit SFR can depend on (at least) two classes of variables.

- ISM **chemical** properties (affect stellar evolution): *Metallicity*

- ISM **physical** properties (affect star formation & IMF): *UV radiation field.*
  *Gas density.*
Origins of GRB Rate Variations

The number of GRBs per unit SFR can depend on (at least) two classes of variables.

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The number of GRBs per unit SFR can depend on (at least) two classes of variables.

- **ISM chemical properties**
  (affect stellar evolution):  
  *Metallicity*
  should correlate with mass/Av.

- **ISM physical properties**
  (affect star formation & IMF):  
  *UV radiation field.*  
  *Gas density.*
  should correlate with SFR/sSFR.
Origins of GRB Rate Variations

Stellar Mass

SFR

Extinction

Specific SFR

Equivalent age 1/sSFR, yr
Origins of GRB Rate Variations

Stellar Mass

SFR

Extinction

Specific SFR

# hosts

GRB rate per unit SFR
Origins of GRB Rate Variations

strong effect

no effect

modest effect

Effect only in youngest galaxies

Stellar Mass

SFR

Extinction

Specific SFR

2

7

3

13

13

8

9

13

13

5
GRBs in submillimeter galaxies?

Densest, most rapidly star-forming galaxies in the Universe are the dusty cores of SMGs. Do we find GRBs there?
GRBs in submillimeter galaxies?

Densest, most rapidly star-forming galaxies in the Universe are the dusty cores of SMGs. Do we find GRBs there?

When GRBs are found in SMGs they are in unobscured regions, not the dusty cores! (e.g. Michalowski+2009)

Perley & Perley 2013: Few JVLA radio detections among dark GRB hosts – these are not luminous SMGs
The number of GRBs per unit SFR can depend on (at least) two classes of variables.

- **ISM chemical** properties (affect stellar evolution): *Metallicity*
  
  should correlate with mass/Av.

- **ISM physical** properties (affect star formation & IMF): *UV radiation field.*
  *Gas density.*
  
  should correlate with SFR/sSFR.
Quantifying metal dependence

Is there a regime where GRB rate variations (due to e.g. metallicity) can be ignored?

\[ \frac{R_{\text{GRB}}}{\text{SFR}} \]

Galaxy mass / ISM metallicity

Galaxy mass / ISM metallicity
Quantifying metal dependence

Apparent F160W magnitude (AB)

(Vega)

Redshift

0.5  1.0  1.5  2.0  2.5  3.0

Galaxies & GRBs @ Cabo del Gata
Quantifying metal dependence

$z = 0.5 - 1.4$

Apparent F160W magnitude (AB) vs. Redshift ($z=0.5-1.4$)
Quantifying metal dependence

$z = 0.5 - 1.4$

Apparent F160W magnitude (AB)

Redshift

Luminosity

Galaxies & GRBs @ Cabo del Gata

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Quantifying metal dependence

$z = 0.5 - 1.4$

Apparent $F_{160W}$ magnitude (AB)

Luminosity

Redshift

GRBs as Tracers of Cosmic Star Formation
No significant luminosity dependence below $M < 10^{9.5}$ $M_\odot$ observed so far – consistent with a $\sim 1/2$ $Z_\odot$ “threshold”.

Quantifying metal dependence

- $R_{\text{GRB}}/\text{SFR}$
- Galaxy mass (ISM metallicity?)
- Galaxy mass (ISM metallicity?)

Luminosity
GRBs at z<2 are **not unbiased tracers of star-formation**.

Consistent with metallicity dependence.

Possible secondary amplification of GRB rate in high-sSFR galaxies?

Rate variation levels off at low-mass end

No further variation below $<10^9 \, M_\odot \, @ \, z\sim 1$

Metallicity “threshold” at $\sim 0.5 Z_\odot$ may be real

Still viable tracers for low masses, z>3? Maybe...

Dark burst hosts are very different from unobscured hosts.

Including both unobscured and obscured bursts in correct proportion is **critical** for statistical analysis and further progress!