GRB 160625B: Evidence for a Gaussian-shaped Jet

Ginny Cunningham
Astronomy PhD Candidate
University of Maryland, College Park

Brad Cenko (NASA/GSFC), Geoff Ryan (UMD/GSFC), Stuart Vogel (UMD), Alessandra Corsi (TTU), Antonino Cucchiara (UVI), Andrew Fruchter (STScI), Assaf Horesh (HUJI), Tuomas Kangas (OKC), Dan Kocevski (NASA/MSFC), Dan Perley (LJMU), and Judy Racusin (NASA/GSFC)
Fermi LAT GRBs are extremely bright.

But are they actually intrinsically brighter or do they just have narrower jets?
Jet breaks reveal information about the burst geometry.

Jet break \( t_{\text{jet}} \) occurs when \( \Gamma = 1/\theta_{\text{jet}} \).

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Things we still don’t know:

How much energy is released by the explosion?

What’s powering their central engines?

What are their local environments like?

How is their jet emission shaped?

And much more...
3 Models:
1: Simple conical top-hat model
2: Gaussian jet structure
3: Gaussian with variable participation fraction of electrons

*Adapted from the LIGO discovery paper

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Eichler & Waxman 2005
Warren, D.C. + 2017, 2018

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GRB 160625B:

Jet break
Beaming angle changes by factor of 2-3

<table>
<thead>
<tr>
<th>Model</th>
<th>Top-Hat</th>
<th>Gaussian (fixed $\xi$)</th>
<th>Gaussian (free $\xi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_v$</td>
<td>[deg]</td>
<td>$0.42^{+0.14}_{-0.09}$</td>
<td>$0.13^{+0.34}_{-0.06}$</td>
</tr>
<tr>
<td>$E_{K,\text{iso}}$</td>
<td>[erg]</td>
<td>$2.3^{+0.5}_{-0.7} \times 10^{54}$</td>
<td>$3.1^{+0.4}_{-0.8} \times 10^{54}$</td>
</tr>
<tr>
<td>$\theta_c$</td>
<td>[deg]</td>
<td>$1.83^{+0.52}_{-0.23}$</td>
<td>$1.26^{+0.34}_{-0.06}$</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>[deg]</td>
<td>-</td>
<td>$1.60^{+0.40}_{-0.11}$</td>
</tr>
<tr>
<td>$n$</td>
<td>[cm$^{-3}$]</td>
<td>$9.6^{+39.0}_{-5.9} \times 10^{-7}$</td>
<td>$3.1^{+11.0}_{-1.1} \times 10^{-6}$</td>
</tr>
<tr>
<td>$p$</td>
<td></td>
<td>$3.0^{+2.0}_{-0.3}$</td>
<td>$0.13^{+0.01}_{-0.07}$</td>
</tr>
<tr>
<td>$\epsilon_e$</td>
<td></td>
<td>$0.12^{+0.05}_{-0.02}$</td>
<td>$0.19^{+0.07}_{-0.02}$</td>
</tr>
<tr>
<td>$\epsilon_B$</td>
<td></td>
<td>$0.16^{+0.10}_{-0.10}$</td>
<td>$0.17^{+0.05}_{-0.09}$</td>
</tr>
<tr>
<td>$\xi$</td>
<td></td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$\eta^a$</td>
<td></td>
<td>$0.56^{+0.08}_{-0.05}$</td>
<td>$0.49^{+0.08}_{-0.03}$</td>
</tr>
<tr>
<td>$E_{\text{rel}}^b$</td>
<td>[erg]</td>
<td>$2.7^{+1.3}_{-0.5} \times 10^{51}$</td>
<td>$1.6^{+0.6}_{-0.1} \times 10^{51}$</td>
</tr>
<tr>
<td>$\chi^2$/dof</td>
<td></td>
<td>1.24</td>
<td>0.99</td>
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<td>Top-Hat</td>
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<tr>
<td>-------------</td>
<td>--------------------------</td>
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<td>------------------------</td>
</tr>
<tr>
<td>$\theta_v$</td>
<td>0.42$_{-0.09}^{+0.14}$</td>
<td>0.13$_{-0.06}^{+0.34}$</td>
<td>3.78$_{-0.52}^{+0.57}$</td>
</tr>
<tr>
<td>$E_{K,iso}$</td>
<td>2.3$_{-0.7}^{+0.5}$ $\times 10^{54}$</td>
<td>3.1$_{-0.8}^{+0.4}$ $\times 10^{54}$</td>
<td>4.2$_{-3.5}^{+24.0}$ $\times 10^{55}$</td>
</tr>
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<td>$E_B$</td>
<td>1.83$_{-0.23}^{+0.52}$</td>
<td>1.26$_{-0.06}^{+0.34}$</td>
<td>3.00$_{-0.57}^{+0.53}$</td>
</tr>
<tr>
<td>$\eta_a$</td>
<td>-</td>
<td>1.60$_{-0.11}^{+0.40}$</td>
<td>4.76$_{-0.63}^{+0.53}$</td>
</tr>
<tr>
<td>$n$</td>
<td>9.6$_{-5.9}^{+39.0}$ $\times 10^{-7}$</td>
<td>3.1$_{-1.1}^{+11.0}$ $\times 10^{-6}$</td>
<td>0.35$_{-0.31}^{+1.71}$</td>
</tr>
<tr>
<td>$p$</td>
<td>2.30$_{-0.02}^{+0.02}$</td>
<td>2.13$_{-0.01}^{+0.01}$</td>
<td>2.10$_{-0.01}^{+0.01}$</td>
</tr>
<tr>
<td>$\epsilon_e$</td>
<td>0.12$_{-0.03}^{+0.05}$</td>
<td>0.19$_{-0.02}^{+0.07}$</td>
<td>0.017$_{-0.014}^{+0.085}$</td>
</tr>
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<td>$\epsilon_B$</td>
<td>0.16$_{-0.10}^{+0.11}$</td>
<td>0.17$_{-0.09}^{+0.05}$</td>
<td>3.9$_{-3.3}^{+21.9}$ $\times 10^{-5}$</td>
</tr>
<tr>
<td>$\xi$</td>
<td>1.0</td>
<td>1.0</td>
<td>0.016$_{-0.013}^{+0.080}$</td>
</tr>
<tr>
<td>$\eta_a$</td>
<td>0.56$_{-0.05}^{+0.08}$</td>
<td>0.49$_{-0.03}^{+0.08}$</td>
<td>0.067$_{-0.057}^{+0.253}$</td>
</tr>
<tr>
<td>$E_{rel}$</td>
<td>2.7$_{-0.5}^{+1.3}$ $\times 10^{51}$</td>
<td>1.6$_{-0.1}^{+0.6}$ $\times 10^{51}$</td>
<td>1.2$_{-0.9}^{+6.5}$ $\times 10^{53}$</td>
</tr>
<tr>
<td>$\chi^2$/dof</td>
<td>1.24</td>
<td>0.99</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Circumburst Density
Extremely low
ISM-like
<table>
<thead>
<tr>
<th>Model</th>
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<tr>
<td>$\theta_v$ [deg]</td>
<td>0.42$^{+0.14}_{-0.09}$</td>
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<td>3.78$^{+0.57}_{-0.52}$</td>
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<td>$E_{K,iso}$ [erg]</td>
<td>$2.3^{+0.5}_{-0.7} \times 10^{54}$</td>
<td>$3.1^{+0.4}_{-0.8} \times 10^{54}$</td>
<td>$4.2^{+24.0}_{-3.5} \times 10^{55}$</td>
</tr>
<tr>
<td>$\rho_0$ [deg]</td>
<td>1.83$^{+0.52}_{-0.23}$</td>
<td>1.26$^{+0.34}_{-0.06}$</td>
<td>3.90$^{+0.57}_{-0.57}$</td>
</tr>
<tr>
<td>$n$ [cm$^{-3}$]</td>
<td>9.6$^{+39.0}_{-5.9} \times 10^{-7}$</td>
<td>3.1$^{+11.0}_{-1.1} \times 10^{-6}$</td>
<td>0.35$^{+1.71}_{-0.31}$</td>
</tr>
<tr>
<td>$p$</td>
<td>2.30$^{+0.02}_{-0.02}$</td>
<td>2.13$^{+0.01}_{-0.01}$</td>
<td>0.35$^{+1.71}_{-0.31}$</td>
</tr>
<tr>
<td>$\epsilon_e$</td>
<td>0.12$^{+0.05}_{-0.02}$</td>
<td>0.19$^{+0.07}_{-0.02}$</td>
<td>0.017$^{+0.085}_{-0.014}$</td>
</tr>
<tr>
<td>$\epsilon_B^a$</td>
<td>0.16$^{+0.11}_{-0.10}$</td>
<td>0.17$^{+0.05}_{-0.09}$</td>
<td>0.007$^{+0.033}_{-0.053}$</td>
</tr>
<tr>
<td>Total Energy $E_{rel}^b$ [erg]</td>
<td>$2.7^{+1.3}_{-0.5} \times 10^{51}$</td>
<td>$1.6^{+0.6}_{-0.1} \times 10^{51}$</td>
<td>$1.2^{+6.5}_{-0.9} \times 10^{53}$</td>
</tr>
<tr>
<td>$\chi^2$/dof</td>
<td>1.24</td>
<td>0.99</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Isotropic Energy

Total Energy

2 orders of magnitude!
Central Engine:

Magnetar? or Collapsar?

$E_{\text{rel}} < 10^{52}$ erg

Beniamini+ 2017
Metzger+ 2018

$E_{\text{rel}} < 10^{54}$ erg

Woosley 1993
MacFadyen & Woosley 1999
GRB 160625B:

\[ E_{\text{rel}} = 1.2 \times 10^{53} \text{ erg} \]

Woosley 1993
MacFadyen & Woosley 1999
Gaussian jet shape resembles that of GRB 170817A.

Jet structure may be independent of central engine?
Preliminary Results: All GRBs prefer lower participation fractions
Fermi GRB Summary:

- We tested three jet structure models on the multiwavelength afterglow of GRB 160625B.
- Derived parameters between top-hat and Gaussian (fixed $\xi$) jet models remain consistent, although Gaussian shape is preferred.
  - $\Theta_c$: ~1 to 4°
  - $E_{\text{rel}}$: $\sim 2 \times 10^{51}$ erg
  - $n$: $\sim 10^{-6}$ cm$^{-3}$
- Smaller values of $\xi$ are preferred yet also dramatically affect the afterglow light curve.
  - $E_{\text{rel}}$: $\sim 1 \times 10^{53}$ erg
  - $n$: $\sim 10^{-1}$ cm$^{-3}$
- 160625B likely prefers a collapsar origin.
- Further analysis on a larger sample of bright LAT-detected GRBs hint at similar trends.
Backup Slides
Gamma-ray Bursts (GRBs)

- Two kinds: short and long
- Bright prompt + long-lasting afterglow
- Visible across EM spectrum
- Beamed emission
- Ultrarelativistic ejecta
Jet breaks reveal information about the burst geometry.

Jet break occurs when $\Gamma = 1/\Theta_{\text{jet}}$.
Multiwavelength Modeling with Afterglowpy:

- Synchrotron Emission
- Semi-Analytical
- MCMC
- Function of viewing angle and jet structure

Adapted from J. Michael Burgess

Intro Motivation Modeling Implications


https://pypi.org/project/afterglowpy/

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Participation Fraction (ξ): fraction of electrons contributing to the observed flux

Intro Motivation Modeling Implications

--- Gaussian
--- top-hat

Radio (6.1 GHz)  Optical (r-band)  X-ray (5 keV)
First test case:
GRB 160625B

Extremely Bright

$E_{\gamma,iso} = 6 \times 10^{54}$ erg

LAT, Swift XRT, Chandra, LCO, Magellan, RATIR, Swift UVOT, VLA, ATCA, +

Alexander, Laskar, Berger + 2017
Troja, Lipunov, Mundell + 2017
Kangas, Fruchter, Cenko + 2020
# Model Comparison:

<table>
<thead>
<tr>
<th>Model 3: Gaussian (free $\xi$)</th>
<th>Model 2: Gaussian (fixed $\xi$)</th>
<th>Model 1: Top Hat</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAIC 1782.7 ± 79.1</td>
<td>1744.3 ± 78.5</td>
<td>-3561.8 ± 167.2</td>
</tr>
<tr>
<td>$\Delta$WAIC/N -</td>
<td>0.10 ± 0.09</td>
<td>-14.5 ± 2.7</td>
</tr>
<tr>
<td>Confidence Level -</td>
<td>$(0.58-1.16)\sigma$</td>
<td>$(2.7-5.3)\sigma$</td>
</tr>
</tbody>
</table>

WAIC: Widely Applicable Information Criterion (Gelman 2013)

$\rightarrow$ Measure of future predictability
Preliminary Results:
Isotropic Energy increases by 1-2 orders of magnitude when participation fraction is allowed to vary.
Preliminary Results:
Circumburst density increases by several orders of magnitude when participation fraction is allowed to vary.
Future work:

VHE follow-up of *Fermi* GRBs

- 3 GRBs have been detected with MAGIC, HESS
  - $\sim1$ TeV

- CTA first light scheduled for 2022
- 10 x more sensitive than VERITAS
  - 100 telescopes