GRB 160625B: Evidence for a Gaussian-shaped Jet

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Abstract

We present multiwavelength modeling of the afterglow from the long γ-ray burst (GRB) 160625B using Markov Chain Monte Carlo techniques of the afterglowpy Python package. GRB 160625B is an extremely bright burst with a rich set of observations spanning from radio to γ-ray frequencies. These observations range from ~0.1 days to >1000 days, thus making this event extremely well suited to such modeling. In this work we compare top-hat and Gaussian jet structure types in order to find best-fit values for the GRB jet collimation angle, viewing angle, and other physical parameters. We find that a Gaussian-shaped jet is preferred (2.7σ–5.3σ) over the traditional top-hat model. Our estimate for the opening angle of the burst ranges from 1°26 to 3°90, depending on jet-shape model. We also discuss the implications that assumptions on jet shape, viewing angle, and particularly the participation a fraction of electrons have on the estimated total relativistic energy of the burst, Eγ, iso.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Relativistic jets (1390)

Supporting material: machine-readable tables

1. Introduction

Long γ-ray bursts (GRBs)12 are among the most violent and energetic phenomena in the universe. Despite observations of thousands of GRBs over the past few decades, key open questions—such as the nature of the central engine and the structure and composition of the relativistic jets—remain unsolved.

One key to unraveling these mysteries lies in accurately measuring their energetics. Estimates of the total relativistic energy released by a GRB can have major implications for constraining their physical characteristics and origins. Precise measurements could potentially distinguish between different progenitor systems. Two popular theories include rotationally powered magnetars (Zhang & Mészáros 2001; Thompson et al. 2004; Metzger et al. 2015) and the collapse of a massive star into a black hole (Woosley 1993; MacFadyen & Woosley 1999; Woosley & Heger 2012).

GRBs are known to be highly collimated explosions with jet opening angles typically between 1° and 10° (Sari et al. 1999; Rhoads 1999). The true value of the intrinsic energy release of a GRB is dependent upon this collimation angle:

\[ E_\gamma = E_{\gamma,\text{iso}}(1 - \cos \theta_j) \approx E_{\gamma,\text{iso}} \theta_j^2 \]

where \( E_\gamma \) is the beaming-corrected γ-ray energy of the burst, \( E_{\gamma,\text{iso}} \) is the uncorrected isotropic γ-ray energy, and \( \theta_j \) is the jet half-opening angle.\(^{13}\) Bloom et al. 2001; Frail et al. 2001. This jet collimation correction can affect the value of \( E_\gamma \) by a factor of 10–100 (Frail et al. 2001). Therefore, a precise measurement of \( \theta_j \) is imperative for understanding the true energetics of GRBs.

Making a precise measurement of the collimation angle can be difficult, however, as it usually requires sustained, detailed, multiwavelength observations of the GRB afterglow and the identification of a “jet-break,” i.e., a change in the temporal slope of the light curve associated with the observer becoming aware of the edge of the jet (Sari et al. 1999; Panaitescu 2007; Kocevski & Butler 2008; Racusin et al. 2009; Goldstein et al. 2016). Alternatively, the energy of the explosion can be inferred via nonrelativistic calorimetry (Frail et al. 2000; Berger et al. 2004). At late times the ejecta slows to a nonrelativistic spherical blast wave and can be modeled independently of the jet collimation angle. This is of course only possible when sufficiently late-time radio data exist.

Here we focus on events detected at GeV energies by the Large Area Telescope (LAT; Atwood et al. 2009) on Fermi.

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12 The primary focus throughout this paper will be on long-duration GRBs, unless otherwise noted.

13 This equation is only valid for the simple top-hat jet. More complicated jet structure types are discussed in Section 3.2.2.
This sample is well suited for studying GRB energetics since Fermi tends to select events with high values of $E_{\gamma,\text{iso}}$. This effect can be partly explained by both the Amati Relation ($E_{\text{peak}} - E_{\gamma,\text{iso}}$; Amati et al. 2009) and also the lower sensitivity of the LAT compared to X-ray instruments. LAT-detected GRBs often display values of $E_{\gamma,\text{iso}} > 10^{53}$ erg (Figure 1; Cenko et al. 2010, 2011; Xu et al. 2013; Perley et al. 2014), and their afterglows can generally be well modeled by a series of more simple power laws (Yamazaki et al. 2020).

We are conducting a campaign to model the broadband behavior of a sample of LAT-detected GRBs. Here we present the methodology and apply this to one example, that of GRB 160625B—an exceptionally bright long GRB at $z = 1.406$ (Xu et al. 2016). Future work will discuss the broader population in the hopes of identifying whether LAT GRBs in fact represent a unique group and, if so, how they differ from the rest of the GRB population (e.g., jet shape, local environments, magnetar versus black hole central engines; Racusin et al. 2011).

Several previous works have already performed detailed afterglow analysis of GRB 160625B (Alexander et al. 2017; Troja et al. 2017; Kangas et al. 2020, hereafter A17, T17, and K20, respectively). We expand on these works by combining and including all available data as well as undertaking new late-time observations with the Very Large Array (VLA). We also expand the analysis by considering additional models for the internal structure of the GRB jet beyond the canonical top-hat model as well as taking into account viewing angle effects, quantifying the uncertainty of derived parameters, and investigating the role individual afterglow parameters, such as the participation fraction, $\xi$, have on the model fitting.

For our modeling of GRB 160625B, we make use of the new afterglowpy software package (Ryan et al. 2020). Afterglowpy is a publicly available open-source Python package for the numerical computation of structured jet afterglows. This package is unique in its ability to test a range of jet structures such as top-hat, Gaussian, and power law while leaving the viewing angle and jet collimation angle as free parameters.

There is evidence to suggest that the interaction between the GRB jet and the surrounding medium could take on a variety of forms—based on numerical simulations (Aloy et al. 2005; Duffell & MacFadyen 2013a; Margutti et al. 2018) and observations of GW170817/GRB 170817A (Lazzati et al. 2018; Troja et al. 2018). In fact, most GRB jets probably deviate significantly from the simple on-axis top-hat model (e.g., Ryan et al. 2015), and Strausbaugh et al. (2019) have already suggested GRB 160625B can be modeled as a structured jet, so it is imperative to consider this when modeling GRB afterglows.

This paper is organized as follows: We describe the available data products and our data reduction methods in Section 2. In Section 3 we define the details of the GRB afterglow modeling. We discuss the implications of our results in Section 4 and summarize our conclusions in Section 5. All error bars correspond to 1σ uncertainties, and we assume a standard Λ cold dark matter (ΛCDM) cosmology (Planck Collaboration 2020) throughout the analysis.

2. Observations and Data Reduction

2.1. Gamma-Ray

The Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009) first triggered on GRB 160625B at 22:40:16.28 UT on 2016 June 25 (UT times are used throughout this work) and again at 22:51:16.03. The burst is characterized by three “subpulses” separated by two relatively quiescent periods over a duration of $t_\text{q} = 460$s (50–300 keV), and the spectral shape of the burst is well modeled by a Band function (Burns 2016). The fluence in the 10–1000 keV bandpass was $(6.4256 \pm 0.0019) \times 10^{-4}$ erg cm$^{-2}$ (von Kienlin et al. 2020).

The Fermi Large Area Telescope (LAT; Atwood et al. 2009) triggered on the second pulse at 22:43:24.82. The GRB location was in the LAT field of view for $\sim 1000$ s after its initial trigger (20 MeV–300 GeV; Dirirsa et al. 2016). The highest-energy photon observed in the rest frame was 15.3 GeV, which occurred $\sim 345$ s after the first GBM trigger (Ajello et al. 2019).
Table 1

| Instrument (day) | Energy (keV) | Flux Density (nJy) | Instrument |
|-----------------|-------------|-------------------|------------|
| 0.12            | 5           | 4787 ± 1076       | Swift/XRT |
| 0.12            | 5           | 4358 ± 981        | Swift/XRT |
| 0.12            | 5           | 5671 ± 1244       | Swift/XRT |
| 0.12            | 5           | 4772 ± 1073       | Swift/XRT |
| 41.31           | 5           | 1.34 ± 0.38       | Swift/XRT |
| 47.16           | 5           | 1.06 ± 0.47       | Swift/XRT |
| 69.76           | 5           | 0.61 ± 0.12       | Chandra/ACIS-S |
| 144.36          | 5           | 0.13 ± 0.03       | Chandra/ACIS-S |

Note. Times are in reference to the first GBM trigger (2016 June 25 22:40:16.28 UTC).

The GRB was also detected by Konus-Wind (9.44 ± 0.16 × 10^{-4} erg cm^{-2}) from 20 keV to 10 MeV (Svinkin et al. 2016), SPI-ACS/INTEGRAL (Kann 2016), and CALET (Nakahira et al. 2016). For the analysis presented here we choose t₀ to be that corresponding to the first GBM trigger.¹⁴

2.2. X-Ray

The Neil Gehrels Swift Observatory (Gehrels et al. 2004) began observing GRB 160625B 2.5 hours after the initial GBM trigger (Evans 2016). The X-ray Telescope (XRT; Burrows et al. 2005) on board Swift observed GRB 160625B for 47 days. XRT data are taken from the publicly available online Swift burst analyzer tool.¹⁵ For details of how these light curves were produced, see Evans et al. (2007, 2009). The hardness ratio appears relatively constant over time, so we assume a single spectrum that can be described as an absorbed power law with the Galactic neutral hydrogen column fixed to 9.76 × 10^{20} cm^{-2} (Willingale et al. 2013). Using a photon index of Γₓ = 1.86±0.09 assuming an intrinsic host absorption of n_{HI, int} = 1.8 × 10^{-21} cm^{-2}, an unabsorbed counts-to-flux conversion factor of 4.4 × 10^{-11} erg cm^{-2} et^{-1}, and a redshift of 1.406 (Xu et al. 2016) we convert the 0.3–10 keV flux light curves to a flux density at an energy of 5 keV. We choose only to include data taken during photon counting mode, which begins 0.1 days after the burst. In addition to the XRT data we include the late-time Chandra observations taken by K20 at 69.8 and 144 days after the burst. All X-ray observations are available in Table 1.

2.3. Optical

One defining feature of GRB 160625B is its extremely bright optical afterglow and the presence of an optical “bump” around the time of the jet-break. Straussbaugh et al. (2019) suggest this excess emission could be the result of an edge-brightened jet, while K20 suggest it could instead be produced by density fluctuations within the circumburst medium or angular brightness differences.

A17 utilized several optical instruments to observe the GRB—the 2 m Faulkes Telescope North (FTN) operated by Las Cumbres Observatory (LCO), the 2 m Liverpool Telescope (LT) at Roque de los Muchachos Observatory (ORM), and the Low Dispersion Survey Spectrograph 3 (LDSS3) at Magellan—ranging from 0.56 to 37 days post-trigger. T17 observed the GRB with the Reionization And Transients InfraRed camera (RATIR) beginning 8 hr after the trigger until it faded beyond detection at ~50 days and also reported u-band observations taken with the Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005) on board Swift. In addition, several observations used in this work were compiled from the Gamma-ray Burst Coordinates Network (GCN) Circulars by Zhang et al. (2018) and appropriately converted to flux densities. Late-time Hubble Space Telescope (HST) observations were reported by K20 71.5 and 140.2 days post-trigger. The flux contribution from the host was already subtracted out by K20, and we account for Galactic extinction in the direction of the GRB, E(B−V) = 0.1107 mag (Schlafly & Finkbeiner 2011), by assuming the extinction law described in Fitzpatrick (1999). All optical observations are available in Table 2.

2.4. Radio

We consolidate previous Karl G. Jansky VLA observations (Program IDs 15A-235 and S81171; PIs: Berger and Cenko, respectively) from 1.37 to 209 days after the burst for the most complete sample of radio data (A17; K20). We obtained additional late-time observations of GRB 160625B taken at 6 GHz (C band) on 2020 February 4 15:14:24 (1319 days post-burst; Program ID SC1031, PI: Cenko) for an on-source integration time of 1.8 hr. The data were reduced using the standard VLA calibration pipeline provided by the Common Astronomy Software Applications package (CASA; McMullin et al. 2007). We use J2049+1003 as the complex gain calibrator and 3C286 as both the bandpass and flux calibrator. Imaging is done using the TCLEAN algorithm in CASA. We do not detect any emission at the afterglow location and so report a 3σ upper limit of 7.4 µJy. We calculate this limit as 3 times the rms uncertainty at the position of the GRB. In addition, we include data from the Australian Telescope

¹⁴ Most other analyses reference t₀ to that of the LAT trigger, but since we are ignoring very early data we consider any differences negligible.
¹⁵ https://www.swift.ac.uk/burst_analyser/00020667/
Compact Array (ATCA) taken by T17 between 4.5 and 29 days post-burst. All radio observations are available in Table 3.

3. Afterglow Modeling

3.1. Basic Tenets

The primary focus of this section is to model the broadband afterglow emission of GRB 160625B with the goal of measuring the total energy output of the GRB central engine, the jet opening angle, and the geometry of the jet structure. Here, we assume the standard fireball model for the afterglow where the observed emission is synchrotron radiation from electrons in the circumburst medium accelerated by the relativistic blast wave (Sari et al. 1998; Granot & Sari 2002).

The emitting electrons are accelerated to a power-law distribution of energies with an index of \(-p\) and a minimum Lorentz factor of \(\gamma_m\). The resulting spectral energy distribution (SED) can be described by a series of power-law segments smoothly broken at three characteristic frequencies—\(\nu_m\), the self-absorption frequency; \(\nu_{\text{sa}}\), the frequency of the lowest energy electron in the distribution; and \(\nu_{\text{c}}\), the cooling frequency. The values of the frequencies depend on the structure of the surrounding medium of the explosion as well as the jet shape, jet microphysics, energy produced, and viewing angle.

Before calculating detailed models, we infer the circumburst density profile via the temporal decline rate of the observations. From \(t \approx 0.1\) days to \(t = 20\) days the optical and X-ray data can be well approximated by a single power law. Then at around 20 days the decay steepens, signifying the jet-break.\(^{16}\)

For the early-time i-band data we find \(\alpha_i = -1.00 \pm 0.02\) and for the early XRT observations we find \(\alpha_X = -1.26 \pm 0.02\). The steepening of the slope between the optical and X-ray observations suggests that the cooling frequency, \(\nu_{\text{c}}\), lies between these two regimes. In the case of a slow-cooling constant-density (interstellar medium (ISM)-like) profile \(\alpha_{\text{ISM}} = \frac{3 - p}{4}\) (\(\nu < \nu_{\text{c}}\)), which yields an estimate for \(p\), the index of the electron energy distribution, of \(2.33 \pm 0.03\) (Granot & Sari 2002). In the slow-cooling wind-like scenario \(\alpha_{\text{wind}} = \frac{(1 - 3p)}{4}\), which yields \(p = 1.67 \pm 0.03\). When \(\nu > \nu_{\text{c}}\) the decline rate can be described by \(\alpha = \frac{(2 - 3p)}{4}\) for both the wind and ISM-like profiles. Using \(\alpha = -1.26 \pm 0.02\) we find \(p = 2.35 \pm 0.03\), consistent with the ISM result. Despite fewer observations available at later times (>20 days) the optical decline rate of \(\alpha_{\text{B late}} = -1.61 \pm 0.16\) produces \(p = 2.15 \pm 0.21\) (\(\alpha = \frac{3p}{4}\)), and the X-ray decline rate of \(\alpha_{X,\text{late}} = -2.10 \pm 0.15\) produces \(p = 2.46 \pm 0.20\) (\(\alpha = \frac{3p-1}{4}\); Ryan et al. 2020). The early- and late-time behavior are consistent; thus, throughout this work we assume an ISM-like density profile for GRB 160625B.\(^{17}\)

There are significant features present in the early-time radio data of GRB 160625B that are likely not related to the forward shock emission (Figure 2). A17 attribute these effects to the combination of a reverse shock and interstellar scintillation. Therefore, when modeling the forward shock we conservatively choose to only include post-jet-break radio data (>20 days) and at frequencies above 10 GHz (except for our late-time observation at 6.1 GHz) to mitigate these effects. A17 found there is negligible extinction due to dust within the GRB host galaxy, and so we choose to ignore those effects in our analysis. Due to a systematic offset between the r- and i-band data of A17 and T17 we choose to only include that of T17 and none from A17 in our forward shock modeling as it is a larger data set and observations were directly compared to the PanSTARRS magnitude system (see also K20).

3.2. Afterglowpy Package

Afterglowpy uses the single-shell approximation to numerically and analytically model a blast wave propagating through an ISM-like circumburst medium as a function of viewing angle and jet type (Ryan et al. 2020). A range of jet structure types have been proposed in the literature—some common examples include variations of top-hat, Gaussian, and power-law models (Mészáros et al. 1998; Rossi et al. 2002; Zhang & Mészáros 2002; Rossi et al. 2004; Zhang et al. 2004; Aloy et al. 2005; Duffell & MacFadyen 2013a; Margutti et al. 2018; Coughlin & Begelman 2020). The exact structure of any one GRB jet may be dependent upon several factors such as the immediate circumburst environment and interactions with the stellar envelope. Compared to other available afterglow modeling codes, e.g., BoxFit; van Eerten et al. (2012) afterglowpy is advantageous for its ability to probe this complex inner structure of the GRB jet.

We employ the statistical sampling techniques of the emcee Python package for Markov Chain Monte Carlo (MCMC; Foreman-Mackey et al. 2013) analysis with the afterglowpy models, as outlined in Troja et al. (2018). Afterglowpy generates samples from the entire posterior distribution for each of the models we consider here in this work. As input, our fit takes broadband fluxes, observation times, and instrument frequencies. As output, it produces samples from the posterior distribution for the viewing angle, \(\theta_v\); the isotropic kinetic energy released by the blast wave, \(E_{K,\text{iso}}\); jet core opening angle, \(\theta_j\); circumburst density, \(n\); the spectral slope of the electron distribution, \(p\); the fraction of shock energy imparted to electrons, \(\epsilon_f\); and to the magnetic field, \(\epsilon_B\).

For initial prior parameters we use the best-fit parameters reported in K20. The assumed prior distributions and bounds

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\(^{16}\) Strausbaugh et al. (2019) place the jet-break slightly earlier during the peak of the optical bump at \(\sim 13\) days

\(^{17}\) A17, T17, K20, and other works come to the same conclusion.
for each parameter can be viewed in detail in Table 3 of Ryan et al. (2020). We assume a log-uniform prior distribution for $E_{k,iso}$, $n$, $E_{b,iso}$, and $\xi$ and a uniform prior distribution for $\theta_c$, $\theta_w$, and $p$. The prior distribution for the viewing angle, $\theta_v$, is constrained by the posterior probability distribution reported in Abbott et al. (2017).

3.2.1. Top-hat Jet Model

We begin by first calculating the simplest model that could describe the outflow geometry, the top-hat. In this scenario, the energy of the jet is independent of angle and there is an instantaneous cutoff in energy at the jet edge:

$$E(\theta) = \begin{cases} E_0 & \theta \leq \theta_c, \\ 0 & \theta > \theta_c. \end{cases}$$

(1)

It is unlikely that a top-hat jet could be viewed far off-axis without a significant change in the appearance of the GRB afterglow (van Eerten et al. 2010; Zhang et al. 2015; Kathirgamaraju et al. 2016). Until recently, the top-hat model was assumed for most GRB analyses.

The covariances and posterior probability distributions of the various parameters are shown in Figure 3. Our best-fit parameters for this model are listed in Table 4 and plotted in Figure 4. We allow the value of $p$ to vary but restrict $\xi < 1/3$ and $\epsilon_b < 1/3$ (Alexander et al. 2017; Laskar et al. 2015). This is done primarily to remove degeneracies within the model fitting; however, we found that if we do not apply the restrictions on these microphysical parameters then the fits tend toward quite unphysical values ($\epsilon_b$ approaches 1.0). Therefore, we see this as further evidence that placing these restrictions is valid in this case.

The parameters derived here imply a beaming-corrected kinetic energy of $E_k = E_{k,iso}(1 - \cos \theta_c) = 1.2 \times 10^{51}$ erg.

3.2.2. Gaussian Jet Model

To probe the jet structure we compare the simple top-hat to a more complex Gaussian model:

$$E(\theta) = \begin{cases} E_0 e^{-\frac{\theta^2}{\theta_w^2}} & \theta \leq \theta_w, \\ 0 & \theta > \theta_w. \end{cases}$$

(2)

where $\theta_w$ is the truncation angle of the Gaussian wings.

Similarly to the top-hat model we again restrict $\xi < 1/3$ and $\epsilon_b < 1/3$. In Gaussian models extended emission from the jet could be viewed at angles beyond $\theta_c$, and so larger values of $\theta_c$ are possible. The best-fit parameters are listed in Table 4 and plotted in Figure 4. The covariances and posterior probability distributions of the parameters are shown in Figure 5.

To calculate the beaming-corrected energy we integrate Equation (2) over both jets:

$$E = 2 \int_0^{\theta_w} \int_0^{2\pi} d\phi \, d\theta \, \sin \theta \, \frac{E(\theta)}{4\pi},$$

(3)
which approximates to

\[ E \sim E_0 \theta_c^2 (1 - e^{-\frac{2\theta_c}{\xi}}). \quad (4) \]

This gives a value for the beaming-corrected kinetic energy of \( E_k = 8.4^{+1.2}_{-0.7} \times 10^{50} \) erg, which is slightly less than that found for the top-hat model.

3.2.3. Gaussian Jet Model with Free \( \xi \)

In the synchrotron afterglow model the emission is driven by a power-law distribution of electrons in the surrounding medium. The participation fraction, \( \xi \), describes the percentage of total electrons that are accelerated by the passing shock wave and contribute to this power-law distribution. 100% participation (\( \xi = 1 \)) is typically assumed in the literature, but simulations have shown \( \xi \) can be as low as \( 10^{-2} \) (Sironi & Spitkovsky 2011; Sironi et al. 2013) and that lower values tend to be more realistic (Warren et al. 2018).

To test this we expand on our Gaussian model and now allow \( \xi \) to vary as a free parameter (Table 4). Notably, the beaming-corrected kinetic energy in this scenario is \( E_k = 1.1^{+0.5}_{-0.9} \times 10^{53} \) erg, two orders of magnitude higher than in the previous cases. Such a high energy density may lead to
Table 4
Best-fit Model Parameters

| Parameter          | Unit | This Work | This Work | This Work | A17 | K20 | T17 |
|--------------------|------|-----------|-----------|-----------|-----|-----|-----|
|                    |      | Top-hat   | Gaussian (fixed ξ) | Gaussian (free ξ) | Top-hat | Top-hat | Top-hat |
| θ_e (rad)          |      | 0.0073 ± 0.0024 | 0.022 ± 0.006 | 0.066 ± 0.018 | ... | 0.012 | ... |
| E_{K,iso} (erg)    |      | 2.3 +0.5 \times 10^{54} | 3.1 ± 0.8 \times 10^{54} | 4.2 ± 3.5 \times 10^{55} | 1.4 ± 1.0 \times 10^{54} | 1.8 \times 10^{54} | 2.0 ± 1.4 \times 10^{54} |
| θ_p (rad)          |      | 0.032 ± 0.004 | 0.022 ± 0.006 | 0.066 ± 0.018 | 0.063 ± 0.003 | 0.059 | 0.042 ± 0.028 |
| n (cm^{-3})        |      | 9.6 ± 2.9 \times 10^{-7} | 3.1 ± 0.11 \times 10^{-6} | 0.352 ± 0.170 | (5 ± 3) \times 10^{-5} | 1.1 \times 10^{-5} | 1.49 ± 0.02 \times 10^{-4} |
| p                 |      | 2.30 ± 0.02 | 2.13 ± 0.01 | 2.10 ± 0.01 | 2.31 ± 0.01 | 2.30 | 2.2 |
| r_p               |      | 0.12 ± 0.05 | 0.19 ± 0.07 | 0.017 ± 0.008 | 0.23 ± 0.07 | 0.13 | 0.10 ± 0.02 |
| β_p               |      | 0.16 ± 0.11 | 0.17 ± 0.09 | 3.9 ± 3.3 \times 10^{-5} | 0.013 ± 0.011 | 0.030 | 0.010 ± 0.009 |
| ξ                 |      | 1.0 | 1.0 | 0.016 ± 0.008 | 1.0 | 1.0 | 1.0 |
| η                 |      | 0.56 ± 0.08 | 0.49 ± 0.03 | 0.062 ± 0.235 | 0.73 ± 0.10 | 0.62 | 0.75 ± 0.16 |
| E_{r,iso} (erg)    |      | 2.7 ± 1.5 \times 10^{54} | 1.6 ± 0.6 \times 10^{54} | 1.2 ± 0.5 \times 10^{53} | 2.3 ± 1.5 \times 10^{51} | 8.3 \times 10^{51} | 6.0 \times 10^{51} |
| χ^2/dof           |      | 1.24 | 0.99 | 0.86 | 1.26 | 8.6 | ... |

Note. Uncertainties are given at 1σ confidence levels. The reduced χ^2 is the minimum over all completed runs.

4. Discussion
4.1. Comparison to Past Works

Previous works have completed similar analyses on GRB 160625B (T17; A17; K20). In each instance the jet is modeled with a conical top-hat structure and there is general agreement on the burst parameters (Table 4). We begin by simulating the light curves with afterglowpy using the model parameters found in A17, T17, and K20. We then compare the results to our own top-hat solution in Figure 8.

K20 utilize the BoxFit package (van Eerten et al. 2012) to model the afterglow, while A17 base their results on the synchrotron model described in Laskar et al. (2014, 2015). In Figure 8 the differences between the models at radio, optical, and X-ray wavelengths can be primarily explained by systematic offsets between afterglowpy and the other...
models used, differences in the data sets used, and the use of additional late-time data that were not available yet for A17 and T17. The largest discrepancies are seen at radio energies. This is partially due to the fewer number of observations available and the potential contamination of the forward shock by other radio effects. Recently Kangas & Fruchter (2019) have noted inconsistencies in observed jet-break times between radio and higher frequencies, thus suggesting that radio afterglow light curves may simply not be well represented by standard afterglow theory. Jacovich et al. (2020) attribute this discrepancy to the lack of proper implementation of Klein–Nishina and effects in most afterglow modeling codes.

4.2. Model Comparison with WAIC

To quantify the differences between our own top-hat and Gaussian models described in Section 3.2 we utilize the widely applicable information criterion (WAIC; Watanabe 2010; Troja et al. 2020). The WAIC score provides an estimate of the expected log predictive density (elpd), i.e., how likely the model is to provide a good fit for future data (Gelman et al. 2013). The elpd in general is quite hard to derive without prior knowledge of the true model, but the WAIC score can be calculated directly from the MCMC statistical samples. In general, it is the difference between WAIC scores, rather than...
the raw WAIC score itself, which is most relevant. A model is considered strongly preferred, i.e., has greater predictive power, over another if the difference between their two WAIC scores is a factor of a few larger than the error on that difference. The uncertainty on the raw WAIC and WAIC difference scores is an estimate of the standard error and can be an underestimate but is usually accurate within a factor of 2 (Bengio & Grandvalet 2004). Therefore, we list a significance range for the confidence level in Table 5.

As discussed in Section 3.2 we first began by directly comparing a top-hat and Gaussian style jet and then exploring the effects that varying the participation fraction, \( \xi \), had on the GRB afterglow. Table 5 shows the model comparison between each of these three cases. Both Gaussian models show a greater predictive power compared to the simpler top-hat model but there is not a significant difference between the two Gaussian models themselves.

4.3. The Participation Fraction, \( \xi \)

In Section 3.2.3 we fit the afterglow of GRB 160625B with a Gaussian jet model but allowed the participation fraction, \( \xi \), to vary. In agreement with the findings of Warren et al. (2018) our model prefers a lower value of \( \xi \sim 0.01 \), rather than total
participation. Clearly, decreasing the participation fraction has dramatic effects on the other physical parameters. If all other parameters are kept fixed then the density of the circumburst environment must increase to provide the necessary number of electrons to produce the observed flux. This causes $q_c$ to increase as the relativistic jet interacts with more material. Increasing the density also results in a faster-evolving shock wave, so $E_K,_{iso}$ must increase to maintain the light-curve shape. Most notably, $\int B_{de}$ decreases by four orders of magnitude due to the lack of accelerated electrons.

Figure 9 illustrates how varying $\xi$ can have dramatic effects on the predicted afterglow light curve. We begin with the best-fit parameter values of the top-hat jet and Gaussian (fixed-$\xi$) jet models from Section 3.2 but fix $\xi$ to three different values—1.0, 0.1, and 0.01—and plot the results. We see the greatest differences at radio energies and at early times in the optical band. Those electrons that pass through the shock wave without being accelerated may increase the opacity to synchrotron self-absorption and also introduce an additional source of emission at very early times at optical wavelengths (~few seconds post-burst) that then remains detectable at radio/millimeter wavelengths for several days or more (Ressler & Laskar 2017). Therefore, constraining the value of $\xi$ is critical for understanding the implications of the total energy budget of the burst (Section 4.7) and the density of the local circumburst environment (Section 4.6).

4.4. Sharp Edge Effects on $p$

In both Gaussian jet fits the spectral slope of the electron distribution, $p$, is significantly lower than $\sim$2.3, which is the value found both analytically (Section 3.1) and in the top-hat model case (Section 3.2.1). When $\xi$ is allowed to vary $p$ decreases from $2.13 \pm 0.01$ to $2.10 \pm 0.01$. This is explained by the favored relationship between $\theta_e$ and $\theta_w$. In both Gaussian models we find $\theta_e/\theta_w \sim 0.8$ meaning the emission does not extend greatly off-axis beyond the primary portion of the jet. Therefore, in slightly off-axis viewing angles the effect of a sharp edge may have a significant impact on the resulting light curve. Emission from one side of the jet reaches the viewer...
The Gaussian model has a higher WAIC score compared to the top-hat case, but there is no new data well, so we use it as the base to compare the others. Each Gaussian curve. To account for the lower number of electrons contributing to the emission the total relativistic energy released must be increased and/or the density of the local circumburst environment must increase as well. Bottom panel: the Gaussian fluxes are normalized by the top-hat model for each value of ξ.

Figure 9. Top panel: we present the best-fit parameter values of the top-hat (solid line) and Gaussian (dashed line) jet models from Section 3.2 but at three fixed values of ξ. The participation fraction, ξ, plays a pivotal role in the GRB afterglow, especially at radio energies. Lowering the value of ξ can have dramatic effects on the light curve. To account for the lower number of electrons contributing to the emission the total relativistic energy released must be increased and/or the density of the local circumburst environment must increase as well. Bottom panel: the Gaussian fluxes are normalized by the top-hat model for each value of ξ.

Table 5
Model Comparison

| Gaussian (Free ξ) | Gaussian (Fixed ξ) | Top Hat |
|-------------------|--------------------|--------|
| WAIC 1782.7 ± 79.1 | 1744.3 ± 78.5 | -3561.8 ± 167.2 |
| Δ WAIC/N | 0.10 ± 0.09 | -14.5 ± 2.7 |
| Confidence | (0.58–1.16)σ | (2.7–5.3)σ |

Note. A WAIC analysis is performed for each model considered. A higher WAIC score indicates better predictability for future data based on the model.

The Gaussian model with ξ free to vary has a higher likelihood of describing new data well, so we use it as the base to compare the others. Each Gaussian model has a higher WAIC score compared to the top-hat case, but there is no strong preference for the free-ξ over the fixed-ξ Gaussian model.

4.5. Viewing Angle Effects

Precise predictions for GRB viewing angles have only become possible within the past few years thanks to the advent of various powerful high-resolution hydrodynamic simulations used both directly and indirectly by codes such as BoxFit (van Eerten et al. 2012), ScaleFit (Ryan et al. 2013), JET (Duffell & MacFadyen 2013b), and afterglowpy (Ryan et al. 2020). Ryan et al. (2015) show that, in fact, most GRBs are probably observed off-axis, and the joint discovery of GW170817/GRB 170817A highlighted just how significant viewing angle effects could be for a single event (Alexander et al. 2018; Lazzati et al. 2018; Troja et al. 2018; Wu & MacFadyen 2018; Xie et al. 2018; Troja et al. 2019; Fong et al. 2019; Lamb et al. 2020).

Underestimating the viewing angle of GRBs may introduce biases in the afterglow model fitting, e.g., by overestimating the beaming width of the jet (van Eerten 2015). To illustrate this we repeat the Gaussian model with the same initial conditions as described in Section 3.2.2, but now we fix θj to an almost on-axis angle of 10−4 radians (Table 6). As a reference we note that Swift GRBs are thought to be observed more off-axis than
this. Typical values of $\theta_c$ range from 0.055 to 0.42 radians (Ryan et al. 2015).

In this case we find that by assuming an on-axis viewing angle we are overestimating $\theta_c$ by a factor of $\sim 4.1$ (compared to the fixed-$\xi$ Gaussian jet model). Utilizing Equation (4) the beaming-corrected kinetic energy in this case is $E_K = 2.0^{+0.4}_{-0.1} \times 10^{51}$ erg. Although we have overestimated the beaming angle the slightly lower estimate for $E_{K,\text{iso}}$ means the beaming-corrected kinetic energy remains consistent with the Gaussian case. Interestingly, the fact that $\theta_{\text{on}}/\theta_c < 1$ indicates a strong preference for a sharp jet edge as in the case of a top-hat jet. However, a WAIC comparison between this case (WAIC $= 1145.7 \pm 197.1$) and the Gaussian jet with fixed-$\xi$ (WAIC $= 1744.3 \pm 78.5$) still shows better predictability and preference for a Gaussian-shaped jet model.

### 4.6. Local Circumburst Environment

Long GRBs are believed to result from the end state of massive stars (Woosley & Bloom 2006). Due to their short lifespan (tens of Myr), these massive stars live and die in the same dense molecular clouds that birthed them. It would appear to be a reasonable assumption to expect the local circumburst densities of GRBs to reflect that of regions of high star formation ($> 1$ cm$^{-3}$). Observationally this is not usually the case, at least when assuming a top-hat jet model and $\xi = 1$ (Laskar et al. 2015).

The derived value of the local circumburst density, $n$, for GRB 160625B is exceptionally low for most models in Table 4. This parameter can be difficult to constrain as it is highly degenerate with other physical parameters in the system. For most GRBs the value of $n$ tends to be between $\sim 10^{-3}$ and $\sim 10^2$ cm$^{-3}$ when assuming $\xi = 1$ (Laskar et al. 2015). Density measurements between Swift and Fermi GRB populations tend to occupy discrete regions of parameter space, thus leading previous studies (e.g., Racusin et al. 2011) to suggest that these two populations may originate in different host environments, although there was not a large enough sample at the time to definitively confirm this.

The preference for ISM-like, low-density local environments may suggest LAT-detected long GRBs originate from lower-metallicity massive stars. This is motivated by the fact that these types of progenitor stars tend to have lower mass-loss rates (Kudritzki et al. 1987; Vink et al. 2001; Woosley et al. 2002). The ability for the relativistic jet to travel unhindered may also prevent the suppression of several radio components and can allow the reverse shock to propagate freely. GRB 160625B is one of only a few long-duration GRBs with a confirmed reverse shock (e.g., Laskar et al. 2013; Perley et al. 2014; Laskar et al. 2016, 2018, 2019).

In the standard afterglow model the circumburst density is intricately connected to other observed physical parameters. As noted in the case of the Gaussian jet with free $\xi$ (Section 3.2.3) our estimate of the local circumburst density is highly dependent upon the participation fraction. Decreasing $\xi$ by a factor of 100 can increase $n$ by upward of five orders of magnitude. Therefore, further work on the impact of the participation fraction, $\xi$, is required before a definitive association can be made between highly energetic long GRBs and massive, metal-poor progenitor stars.

### 4.7. Energetics and Central Engine

One of the main goals of this and future work will be calculating the beaming-corrected energy released by the GRB and especially how that relates to the physics of the central engine. Currently, two popular progenitor models are favored to explain the central engines of long GRBs: magnetars and black hole systems.

The spin-down of a newborn millisecond pulsar could potentially power a long GRB via a Poynting-flux-dominated relativistic outflow (Zhang & Mészáros 2001; Thompson et al. 2004). These magnetars are limited by their finite reserve of rotational energy. For a neutron star with a mass limit of $\sim 2M_\odot$, a radius of 10 km, and a spin period of about 1 ms places a cap on the available energy at $\sim 10^{52}$ erg (Metzger et al. 2007, 2011). This energy cap can be increased in the case of “supramassive” neutron stars that have been stabilized by centrifugal forces and therefore could accommodate rotational energies of up to $10^{53}$ erg (Metzger et al. 2015). However, Beniamini et al. (2017) and Metzger et al. (2018) have recently shown that the true reservoir of available energy is unlikely to reach beyond $\sim 10^{52}$ erg and so the magnetar model is in strong tension with at least the most energetic long GRBs.

In the second scenario, a black hole is formed in the immediate aftermath of the death of a massive star (Woosley 1993; MacFadyen & Woosley 1999; Woosley & Heger 2012). Stellar material accreting back onto the newly formed black hole may power relativistic jets. The jets burrow through the stellar envelope and provide an outlet for relativistic material to escape (Morseny et al. 2007). The typical 10–100 s durations of long GRBs correspond to the freefall time of the star’s helium core. Unlike magnetars, these “collapsars” have much less stringent caps on the potential energy that could be extracted. Theoretical predictions can easily produce energy releases greater than $10^{53}$ erg.

Previous estimates of the total relativistic energy ($E_{\text{tot}} = E_r + E_K$) produced by GRB 160625B range from (2.3–8.3) $\times 10^{51}$ erg when assuming $\xi = 1$ (Table 4). This is approaching but still within the upper limit of the magnetar model. We found in Section 3.2.2 that modeling the jet as a Gaussian rather than a top-hat leads to an estimate of the total relativistic energy that is below this range. Clearly, based on energetic arguments alone, we cannot rule out either the magnetar or collapsar model as progenitors. However, as noted in Section 3.2.3, assuming the participation fraction of electrons is unity is unlikely to be realistic. In agreement with K20, we find that more reasonable lower values of $\xi$ produce an estimate of the total relativistic energy that is two orders of magnitude higher (Figure 9). This value can still be reasonably accommodated by the collapsar model but is in strong tension with the energy cap expected from a magnetar. Regardless, it serves to show that without a better understanding of the participation fraction it will be difficult to draw robust conclusions regarding the progenitor.

### 5. Conclusions

With this work we have performed a case study of GRB 160625B to show the benefits of detailed multiwavelength afterglow modeling as it pertains to understanding GRB energetics and environments. We modeled observations from radio to X-ray wavelengths spanning 0.1–1319 days post-trigger. Using the standard afterglow framework we derived
values for several physical parameters pertaining to the burst and performed a comparison between top-hat and Gaussian jet structure models. Our main conclusions can be summarized as follows:

1. We fit GRB 160625B with a top-hat jet via the afterglowpy modeling package. We find general agreement in the afterglow parameters with previous top-hat jet models.
2. Next, we fit the afterglow with a Gaussian-shaped jet. Although the derived density, kinetic energy, and other microphysical parameters remain consistent with the top-hat case we find that this jet shape is strongly preferred.
3. Finally, we considered how allowing more freedom for the participation fraction, ξ, affects the afterglow parameters. This change had the most dramatic effect and resulted in a density that is 5 orders of magnitude higher, a value of γ that is 4 orders of magnitude lower, and a total relativistic energy that is 2 orders of magnitude higher. This has important implications for constraining the GRB local circumburst environment, central engine, and burst energetics.

Given that our models include several highly degenerate parameters it can be challenging to distinguish between their various subtleties. In Figure 10 we show how varying the viewing angle, θv, impacts the burst afterglow for both top-hat and Gaussian jet structures. There exists an offset in flux density at late times between the two models that is independent of wave band or viewing angle. Therefore the detection of GRBs viewed substantially off-axis (“orphan afterglows”) may not be strictly necessary and future multi-wavelength observations at very late times could help further reinforce the preference for a Gaussian-shaped jet over a top-hat jet.

In future work we plan to continue our analysis on the afterglow modeling of bright LAT-detected long GRBs. These events typically have abundant data and also tend to be observed in low-density environments, thus providing an excellent sample for comparing jet structure models. We will use the results to expand on the arguments discussed here and create a comprehensive sample of well-documented LAT long GRBs and their general properties.

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**References**

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, *Natur*, 551, 85
Ajello, M., Arimoto, M., Axelsson, M., et al. 2019, *ApJ*, 878, 52
Alexander, K. D., Laskar, T., Berger, E., et al. 2017, *ApJ*, 848, 69
Alexander, K. D., Margutti, R., Blanchard, P. K., et al. 2018, *ApJL*, 863, L18
Aloy, M. A., Janka, H. T., & Müller, E. 2005, *A&A*, 436, 273

![Figure 10](https://example.com/figure10.png)

**Figure 10.** Top panel: here we calculate the afterglow light curves for both a top-hat (solid line) and Gaussian (dashed line) jet structure at various points within the beam. We fix θv in the top-hat model so that E_x remains the same in both models. All other parameters besides θv and θc are the same as listed in Table 4. Viewing a GRB off-axis has the greatest affect at early times as this is when edge effects are most noticeable. The differences between Gaussian and top-hat models are most apparent at later times. Bottom panel: the Gaussian fluxes are normalized by the top-hat models for each viewing angle.
