The Jet Opening Angle and Event Rate Distributions of Short Gamma-Ray Bursts from Late-time X-Ray Afterglows

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Abstract

We present a comprehensive study of 29 short gamma-ray bursts (SGRBs) observed ±0.8–60 days postburst using Chandra and XMM-Newton. We provide the inferred distributions of the SGRB jet opening angles and true event rates to compare against neutron star merger rates. We perform a uniform analysis and modeling of their afterglows, obtaining 10 opening angle measurements and 19 lower limits. We report on two new opening angle measurements to compare against neutron star merger rates. We perform a uniform analysis and modeling of their afterglows, but also enabled associations to host galaxies and subsequent redshifts (e.g., Berger 2006; Wainwright et al. 2007; Berger 2009; Fong et al. 2022; Connor et al. 2022).

1. Introduction

Short γ-ray bursts (SGRBs) are explosions characterized by the short duration of their pulses ($T_{90} \lesssim 2$ s) and the hardness of their spectra (Kouveliotou et al. 1993). Monitoring of the synchrotron “afterglow” (e.g., Rees & Meszaros 1992; Meszaros & Rees 1993; van Paradijs et al. 2000) from radio to X-rays provides unique information about the burst energetics, environment density, and opening angles of the highly collimated, relativistic “jet” launched by the central engine (e.g., Rhoads 1997; Panaitescu & Kumar 2002; Piran 2005). The joint power of the Fermi Gamma-ray Space Telescope (Fermi; GLAST Facility Science Team et al. 1999) and the Neil Gehrels Swift Observatory (Swift; Gehrels et al. 2004) has been fundamental in their discovery and arcsecond-scale localizations (e.g., Lien et al. 2016; von Kienlin et al. 2020), as well as facilitating the immediate observational follow up of more than 100 SGRBs (e.g., Evans et al. 2007; Kann et al. 2011; Margutti et al. 2013; D’Avanzo et al. 2014; Fong et al. 2015a). These studies have not only provided insightful information about their afterglows, but also enabled associations to host galaxies and subsequent redshifts (e.g., Berger 2006; Wainwright et al. 2007; Berger 2009; Fong et al. 2010; Church et al. 2011; Berger 2014; Fong et al. 2022; Nugent et al. 2022; O’Connor et al. 2022).

One of the most important parameters in determining the energy scales, rates, and different progenitor channels of SGRBs is the opening angle of the relativistic outflow (e.g., Frail et al. 2001; Fong et al. 2015a; Mandhai et al. 2018), which can be inferred from afterglow light curves. The opening angle is key in the determination of the true energy scale and rates of these events (e.g., Frail et al. 2001; Fong et al. 2015a; Mandhai et al. 2018), which are fundamental properties that can help differentiate between potential progenitor channels. Considering an observer aligned with the jet axis, the jet opening angles can be calculated from the detection of...
temporal steepenings, or “jet breaks” in broadband afterglow light curves (Piran 1999; Rhoads 1999; Sari et al. 1999; Panaitescu 2005).

In this effort, Swift has played an essential role facilitating X-ray follow up of SGRB afterglows (Evans et al. 2007, 2009; Nysewander et al. 2009; Racusin et al. 2009; Margutti et al. 2013), especially at \( \lesssim 1 \) day after the burst trigger. However, SGRB afterglows are generally fast-fading, less energetic than long-duration GRBs, and hence are significantly fainter beyond 1 day (e.g., Gehrels et al. 2008; Kann et al. 2010; Berger et al. 2013; Fong et al. 2015a), when jet breaks potentially take place. Therefore, dedicated deep monitoring campaigns with the sensitivity of the Chandra X-ray observatory (Chandra; Weisskopf et al. 2000) and the X-ray Multi-Mirror Mission Newton (XMM-Newton; Jansen et al. 2001) are necessary to detect jet breaks or place meaningful limits on their collimation. These observations are often supported by joint observations in the optical and radio bands (e.g., Nicuesa Guelbenzu et al. 2012; Fong et al. 2014, 2015a; Troja et al. 2016; Lamb et al. 2019; Troja et al. 2019; Fong et al. 2021). So far, a handful of SGRB jet opening angles of \( \approx 2^\circ–7^\circ \) have been measured (e.g., Burrows et al. 2006; Soderberg et al. 2006; Fong et al. 2012; Troja et al. 2016; Lamb et al. 2019; O’Connor et al. 2021), whereas for the remaining cases, lower limits of \( \gtrsim 4^\circ–25^\circ \) have been inferred (e.g., Fong et al. 2015a; Jin et al. 2018; Rouco Escorial et al. 2021). A priori, not much is known about the general description for jet formation and structure (e.g., Blandford & Znajek 1977; Granot & Sari 2002; Rossi et al. 2002; Rosswo & Ramirez-Ruiz 2002; Ruiz et al. 2016; Lamb et al. 2021; Margutti & Chornock 2021; Gottlieb et al. 2022), nor about the true distribution of SGRB jet opening angles (e.g., Sari et al. 1999; Mészáros & Rees 2001; Zhang et al. 2003), and therefore, not about the real event rate distribution.

Previous studies have shown that SGRBs release kinetic energies of \( \approx 10^{49} \) erg and explode in low-density environments, i.e., \( \approx 10^{-3}–10^{-2} \) cm\(^{-3} \) (Nakar 2007; Nicuesa Guelbenzu et al. 2012; Berger 2014; Fong et al. 2015a), commensurate with their significant offsets from their host galaxies (Fong & Berger 2013; Fong et al. 2022; O’Connor et al. 2022). The discovery of the first binary neutron star (BNS) merger gravitational-wave event, GW170817 (Abbott et al. 2017a), in conjunction with SGRB 170817A (e.g., Abbott et al. 2017a; Goldstein et al. 2017; Savchenko et al. 2017), and the kilonova AT2017gfo (Margutti & Chornock 2021, and references therein), provided the first direct evidence that at least some SGRBs originate from BNS mergers. In addition, the jet of GW170817 was observed off axis (e.g., Lamb & Kobayashi 2017; Alexander et al. 2018; D’Avanzo et al. 2018; Margutti et al. 2018; Troja et al. 2018; Xie et al. 2018; Hajela et al. 2019), establishing a precedent on the study and comparison of structured jet properties against those of cosmological SGRBs, which are viewed on axis. If observed on axis, GRB 170817A’s properties are consistent with those of cosmological SGRBs (e.g., Duan et al. 2019; Salafia et al. 2019; Wu & MacFadyen 2019), but require a structured outflow (Margutti & Chornock 2021). On the other hand, the first gravitational waves produced by neutron star–black hole (NS–BH) mergers (GW200105 and GW200115) were detected during the O3 run of Advanced LIGO/Virgo in 2021 (Abbott et al. 2021b); however no electromagnetic counterparts to either detection were identified (e.g., Antier et al. 2020; Coughlin et al. 2020; Anand et al. 2021; Dichiara et al. 2021; Paterson et al. 2021; Rastinejad et al. 2022). Furthermore, events such as GW190426 and GW191219 were identified as low-significance NS–BH merger detections in the LIGO/Virgo GWTC-2 (Abbott et al. 2021a) and GWTC-3 (The LIGO Scientific Collaboration et al. 2023) catalogs, respectively. Against this backdrop, the true fractions of BNS and NS–BH mergers which launch successful relativistic SGRB-like jets is still uncertain.

In the coming years, the continued upgrades of gravitational-wave detectors (e.g., Advanced LIGO/Virgo/KAGRA; Abbott et al. 2020a) will refine the localization of gravitational-wave events and significantly increase the number of compact binary merger detections. One can use a combination of the SGRB event rate, the BNS/NS–BH merger rates constrained by the detection of gravitational waves, and the Galactic compact binary merger rates to place constraints on the fraction of BNS and NS–BH mergers that produce SGRBs.

Making use of all the available X-ray information collected by Chandra and XMM-Newton for Swift SGRBs detected since 2005, we perform a comprehensive study of these bursts. Utilizing the broadband afterglow information of these events available in the literature, we constrain their energetics, circumburst densities, and jet opening angles. We use the distribution of these opening angles to derive the true event rate of SGRBs and compare it with the observed and theoretically predicted NS merger rates. In Section 2, we introduce the SGRB sample. In Section 3, we describe the uniform reduction and analysis of the X-ray data. In Section 4, we model the temporal afterglow behavior for each burst in our final sample of 29 SGRBs, and use the broadband information of each event to constrain the energetics and circumburst densities. In Section 5, we present the distribution of SGRB jet opening angles, energy scales, and event rates derived from our final sample. In Section 6, we discuss the implications of our findings on the energy scales and jet launching mechanisms, as well as compare our SGRB rate estimates with the BNS and NS–BH merger rates. In Section 7, we summarize the main results. In the Appendix, we present the models used for fitting the afterglow light curves, and further explain the statistical test used to determine the best-fit model. We also present a panel with the X-ray observations of SGRB 130603B that shows the X-ray afterglow of this burst and the contribution of a contaminating source.

The cosmology employed in this paper is standard, with \( H_0 = 69.6 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_M = 0.286 \), and \( \Omega_{\text{vac}} = 0.714 \) (Bennett et al. 2014). All the optical observations have been transformed to the AB magnitude system and corrected for Galactic extinction in the direction of the burst (Schlafly & Finkbeiner 2011). Unless otherwise noted, uncertainties on the median values correspond to the 16th and 84th percentiles of the full distribution.

2. The SGRB Sample

In this paper, we present an analysis of SGRBs that meet all the following criteria:

1. **Bursts classified as short, or short with extended emission (SGRB-EE).** Generally, we select bursts with Swift/BAT durations \( T_9 \lesssim 2 \) s (15–350 keV). We also include in the sample the following verified SGRB-EE events or events with potential EE (Lien et al. 2016): GRB 050724A, with an initial hard, short pulse of \( \approx 0.25 \) s and a soft, long component longer than 100 s in the light curve (Barthelmy et al. 2005; Krimm et al. 2005), and GRBs 080503 (Perley et al. 2009), 101219A (Krimm et al. 2010), 150424A
Jet breaks are achromatic and temporal steepening features in afterglow light curves (e.g., Sari et al. 1999). However, we observe that the optical and radio monitorings are not as consistent as in the X-ray band for all the events in our sample (with some exceptions, e.g., GRBs 130603B, 180418A, 200522A, and 211106A): we find either sparse observations and upper limits, or different optical filters and radio frequencies. Therefore, we only use the X-ray light curves, which are available and better sampled for all events, to calculate the jet-break times or to obtain upper limits on them.

Based on the initial SGRB sample published by Fong et al. (2015a), and the SGRBs or SGRB-EE events detected by either Swift/BAT or Fermi/GBM between 2015 and 2021, we find a total number of 118 SGRBs or SGRB-EEs, out of which 90 were followed by Swift/XRT and have clear X-ray afterglow detections. Applying our second criterion, the group of 90 SGRBs is reduced to 32 events observed by Chandra, XMM-Newton, or both observatories at late times. We exclude GRBs 050813, 161104A, and 210919A since their XRT light curves were only sampled by a single bin, and even in conjunction with the late-time observations, do not allow for reliable light-curve modeling. All our criteria are ultimately met by 29 SGRBs that comprise our final sample. We collect a total of 60 late-time observations across all events in the sample: 18 bursts were observed by Chandra, four by XMM-Newton, and seven additional bursts were monitored by both observatories. We present a uniform analysis of the late-time X-ray afterglow information of the 29 SGRBs, with 10 bursts not being covered in the published, peer-reviewed literature: GRBs 150423A, 150831A, 170728B, 180727A, 191031D, 200411A, 201006A, 210919A, and 210726A. In Figure 1, we show that Chandra and XMM-Newton observations are critical in both the characterization of the X-ray behavior of SGRBs and the identification of jet breaks in the light curves (see Section 5) at \( \delta t \geq 0.8 \) days when Swift’s sensitivity is insufficient to follow up the faint X-ray afterglows.

We list the basic properties such as X-ray positions, durations, and redshifts of the 29 SGRBs in our sample and their available X-ray afterglow information from each X-ray observatory in Table 1. Our sample has redshifts of \( z \sim 0.134–2.211 \), which are representative of nearly the entire range of SGRBs (e.g., Fong et al. 2022; Nugent et al. 2022; Perley et al. 2009).
O’Connor et al. (2022). Eighteen of the events have confirmed spectroscopic redshifts from their host galaxies while six have photometric redshifts. Two bursts have constrained redshift intervals (GRBs 111002A and 211106A), one case (GRB 150423A) has a redshift determined from its afterglow, and two events have an inconclusive host galaxy association (Fong et al. 2022). We include the redshift values in our subsequent analysis to put constraints on the explosion energetics and circumburst density properties of each burst in the sample, as well as determining their half-opening angles ($\theta_i$; referred as opening angle hereinafter, see Section 5).

3. X-Ray Observations and Analysis

We perform a systematic reduction of all the available Chandra and XMM-Newton observations in the SGRB sample in order to model their X-ray spectra and obtain their unabsorbed X-ray flux afterglow light curves.

3.1. Chandra Observations

First, we collected the 24 Chandra observations out of 47 exposures that our team obtained through dedicated target of opportunity (ToO) and director discretionary time (DDT) programs (Pls: Berger, Fou, Rouco Escorial, and Schroeder; Table 2) to follow up SGRB afterglows at late times. Additionally, we retrieved archival data of the other SGRBs (23 out of 47 exposures) in our sample utilizing the Chandra Search and Retrieval Interface (ChaSer18). All Chandra observations in this sample were obtained using the ACIS-S detector, except for GRB 110112A, which was observed with the HRC. We used the CIAO 4.12 software package (Fruscione et al. 2006) with the CALDB 4.9.0 calibration database files for reducing the data. We reprocessed the data using the chandra_repro task to obtain new Level II event files, and filtered each observation to omit time intervals with high background flares (using threshold rates of $\geq 0.5$–0.6 counts s$^{-1}$ in the 0.5–7 keV range for the ACIS-S detector). Then we ran the CIAO source detection tool, WAVDETECT, to perform a blind search for X-ray sources. We used the default wavelet scale values (2 and 4) to detect small features, and a threshold (sigthresh) of 10$^{-6}$ for identifying a source pixel.

Once we obtained a list of all detected X-ray sources for a given observation, we searched the Swift/XRT enhanced afterglow positions for a spatially coincident Chandra source. In case of a positive match, we calculated the 1$\sigma$ uncertainty on the afterglow position as:

$$\sigma_{\text{tot}} = \sqrt{\sigma_{\text{centroid}}^2 + \sigma_{\text{astro}}^2} ,$$

where $\sigma_{\text{centroid}}$ is the afterglow centroid 1$\sigma$ uncertainty provided by WAVDETECT (typically $\approx 0\dagger02$–0\dagger3) and $\sigma_{\text{astro}}$ is the Chandra absolute astrometric uncertainty (1$\sigma$) of 0\dagger6.19

The positions and their uncertainties are listed in Table 1.

We found that 14 SGRBs have at least one afterglow detection with Chandra.20 For these bursts, we obtained the count rates and spectral information of their afterglows using circular source regions centered on the Chandra afterglow positions, with radii that varied between 1\dagger5 and 3\dagger0 depending on the extension of the source. For the background count rates and spectra, we used source-free annuli centered on the source with default inner and outer radii of 30\dagger and 60\dagger, respectively. In some cases, we needed to vary the sizes of these regions slightly to avoid neighboring sources.

For each detection, we extracted the afterglow net count rate using the CIAO/DMEXTRACT tool in the Chandra 0.5–7 keV energy range. We also generated source and background spectra, together with their ancillary response files (arf and redistribution matrix files (rmf) using the SPECEXTRACT tool. In the case of nondetections, we converted the extracted Chandra count rates (0.5–7 keV) from a 1\dagger5 circular region centered on the XRT positions into 3$\sigma$ count-rate upper limits using Poissonian confidence levels according to Table 1 in Gehrels (1986).

In addition, we detected neighboring X-ray sources close to the afterglow positions of GRBs 130603B, 180418A, 200522A, and 210726A. These sources could not be resolved in the source regions of the Swift/XRT or XMM-Newton/EPIC observations21 and fall within the SGRB point-spread function (PSF). To correct the SGRB afterglow light curves from the contributing X-ray flux of these contaminants, we extracted their spectra and modeled them to account for their spectral behavior in our analysis (see Section 3.4).

3.2. XMM-Newton Observations

Similarly to Section 3.1, we gathered our seven XMM-Newton observations of SGRBs from our ToO dedicated program (PI: Fou; Table 2). For the remaining six observations of SGRBs that our group did not obtain, we searched the XMM-Newton Science Archive (XSA22) for public observations. All EPIC observations were obtained utilizing the pn and both MOS detectors. We used the XMM-Newton Science Analysis System (SAS; version 18.0.0; Gabriel et al. 2004) for reducing and analyzing the observations. First, we produced calibrated event lists by running the EMPROC and EPPROCS tasks and filtered them for any background flaring activity. We use threshold rates of $\geq 0.4$–0.5 counts s$^{-1}$ in the 10–12 keV range for the pn detector, and threshold rates of $\geq 0.25$–0.3 counts s$^{-1}$ in the $>$10 keV range for the MOS detectors to filter out intervals of high background.

Next, we performed a blind search for X-ray sources running the EDETECTCHAIN23 routine. This SAS task performs a simultaneous search for EPIC sources on background-filtered images extracted in five energy bands (0.2–0.5 keV for MOS and 0.3–0.5 keV for pn, and 0.5–1 keV, 1–2 keV, 2–4.5 keV, and 4.5–12 keV for all detectors) and generates a final list of detected sources on a background-filtered image representing the full energy range. We then searched for detected sources coinciding with the Swift/XRT positions; for relevant detected sources, we calculated the positional uncertainty (Equation (1)), where $\sigma_{\text{centroid}}$ is provided by EDETECTCHAIN and $\sigma_{\text{astro}}$ = 1\dagger5, i.e., the XMM-Newton systematic error (Rosen et al. 2016; de la Calle Pérez et al. 2021).

We detected afterglows in at least one observation for eight SGRBs. We extracted the count rates and spectra of the sources.

21 Even though GRBs 180418A and 200522A have already published data sets corrected for these effects (O’Connor et al. 2021; Rouco Escorial et al. 2021; respectively), we reprocess this analysis for consistency.
22 http://nxsa.esac.esa.int/nxsa-web/#search
23 https://www.cosmos.esa.int/web/xmm-newton/sas-thread-src-find
## Table 1

Basic Properties of SGRBs with Late-time X-Ray Observations

| GRB     | R.A.          | Decl.          | $\sigma_{\text{pos}}$ (arcsec) | $T_{90}$ (s) | $z$ | Observatory | Redshift References |
|---------|---------------|----------------|-------------------------------|-------------|-----|-------------|---------------------|
| 050509B | 12h36m13.7"   | +28°59'03.3"   | 5.4                          | 0.0240 ± 0.0089 | 0.225" | Y           | Y                   | Bloom et al. (2006) |
| 050709A | 23h01m26.9"   | -38°58'39.6"   | 0.4                          | 0.07 ± 0.01  | 0.160" | N           | N                   | Villasenor et al. (2005); Fox et al. (2005) |
| 050724A | 16h24m44.3"   | -27°32'27.5"   | 0.6                          | 98.7 ± 8.6 (EE) | 0.257" | Y           | N                   | Berger et al. (2005) |
| 051221A | 21h54m48.6"   | +16°53'27.0"   | 0.6                          | 1.39 ± 0.20  | 0.546" | Y           | N                   | Soderberg et al. (2006) |
| 100117A | 00h45m04.7"   | -01°35'42.1"   | 2.3                          | 0.292 ± 0.032 | 0.915" | Y           | Y                   | Fong et al. (2011) |
| 101219A | 04h58m20.4"   | -02°32'23.2"   | 1.5                          | 0.83 ± 0.18 (EE) | 0.718" | Y           | Y                   | Fong et al. (2013) |
| 110112A | 21h59m43.7"   | +26°27'24.4"   | 1.9                          | 0.52 ± 0.15  | ...   | Y           | Y                   | Fong et al. (2022) |
| 111117A | 19h08m12.5"   | -38°00'43.0"   | 0.6                          | 0.384 ± 0.093 | 0.5–1.5 | Y           | Y                   | Selsing et al. (2018) |
| 120804A | 15h35m47.5"   | -28°46'55.9"   | 0.6                          | 0.808 ± 0.083 | 1.05"  | Y           | Y                   | Fong et al. (2022) |
| 130603B | 11h28m48.4"   | +17°04'18.4"   | 1.8                          | 0.176 ± 0.024 | 0.357" | Y           | Y                   | Fong et al. (2013) |
| 140930B | 15h52m03.2"   | +27°36'10.9"   | 0.6                          | 0.296 ± 0.034 | 0.353" | Y           | Y                   | Fong et al. (2022) |
| 150101B | 12h52m05.0"   | -10°56'02.8"   | 0.6                          | 0.0120 ± 0.0089 | 0.134" | Y           | Y                   | Fong et al. (2016) |
| 150423A | 14h46m18.9"   | +12°17'00.3"   | 1.8                          | 0.216 ± 0.028 | 1.392" AG | Y           | Y                   | Fong et al. (2022) |
| 150433A | 10h09m13.3"   | -26°37'51.2"   | 1.4                          | 81 ± 17 (EE) | 0.3"   | Y           | Y                   | Fong et al. (2022) |
| 150831A | 14h44m50.8"   | -25°38'06.4"   | 1.9                          | 0.92 ± 0.12  | 1.18"  | Y           | N                   | Castro-Tirado et al. (2015); Schroeder & Margalit (2020) |
| 160624A | 22h00m46.2"   | +29°38'37.8"   | 2.0                          | 0.19 ± 0.14  | 0.48"  | Y           | Y                   | Fong et al. (2022) |
| 160821B | 18h59m54.7"   | +62°23'30.4"   | 2.1                          | 0.480 ± 0.073 | 0.162" | Y           | Y                   | O’Connor et al. (2021); Fong et al. (2022) |
| 170725B | 15h51m55.4"   | +70°07'20.6"   | 1.7                          | 48 ± 26 (EE) | 1.272" | Y           | Y                   | Lamb et al. (2019); Troja et al. (2019); Fong et al. (2022) |
| 180418A | 11h20m29.2"   | +24°55'59.2"   | 0.6                          | 1.90 ± 0.76  | 1.56"  | Y           | Y                   | Fong et al. (2022) |
| 180727A | 23h06m40.0"   | -63°03'07.1"   | 0.6                          | 1.06 ± 0.23  | 1.95"  | Y           | Y                   | Fong et al. (2022) |
| 191031D | 18h53m09.5"   | +47°38'38.6"   | 2.0                          | 0.288 ± 0.047 | 1.93"  | Y           | Y                   | Fong et al. (2022) |
| 200411A | 03h10m39.4"   | -52°19'03.7"   | 1.4                          | 0.220 ± 0.045 | 0.82"  | Y           | Y                   | Fong et al. (2022) |
| 200522A | 00h22m43.7"   | 00°16'56.9"    | 0.7                          | 0.616 ± 0.079 | 0.554" | Y           | Y                   | Fong et al. (2021) |
| 201006A | 04h07m34.3"   | +65°09'52.4"   | 2.1                          | 0.49 ± 0.09(†) | ...   | Y           | Y                   | Fong et al. (2021) |
| 210726A | 12h53m09.7"   | +19°11'24.5"   | 0.6                          | 0.59 ± 0.11(‡) | 0.37"  | Y           | Y                   | Fong et al. (2022) |
| 210919A | 05h21m01.0"   | +01°18'42.1"   | 4.7                          | 0.16 ± 0.03(§) | 0.242" | Y           | Y                   | Fong et al. (2022) |
| 211106A | 22h54m20.5"   | -53°13'51.4"   | 0.6                          | 1.7 ± 0.1(¶)  | 0.51-1  | Y           | Y                   | Laskar et al. (2022) |

**Notes:**

- **Column (1):** GRB name.
- **Columns (2)–(4):** R.A., decl., and positional uncertainty of the X-ray afterglow, respectively (see Section 3).
- **Column (5):** the duration ($T_{90}$) information is retrieved from [swift.gsfc.nasa.gov/results/hatetracer/](https://swift.gsfc.nasa.gov/results/hatetracer/), except for the $T_{90}$ values of GRBs 050509B, 180418A, 201006A, 210726A, 210919A, and GRB–211106A, which appear in Villasenor et al. (2005), Fox et al. (2005), Rouco Escorial et al. (2021), Barthelmy et al. (2020), Palmer et al. (2021), Barthelmy et al. (2021), and Laskar et al. (2022), respectively.
- **Column (6):** redshifts ($z$), where “sp” denotes spectroscopic, “sp,AG” indicates spectroscopic afterglow, and “ph” refers to photometric redshifts. Columns (7)–(9): “Y” (yes) and “N” (no) indicate whether or not the burst position was observed by that observatory. Column (10): references used to retrieve the redshift information.
- **GRB 050509B was observed with XMM-Newton, however none of the observations were useful to retrieve afterglow information.**
- **HETE source.**
- **SGRB detected by INTEGRAL and confirmed by Swift/BAT-GUANO (Tohuvavuhou et al. 2021).**
### Table 2

| GRB     | Mission | PI     | ObsID | $\delta$ (days) | Exposure (ks) | $N_{\text{Htot}}$ $(10^{22} \text{ cm}^{-2})$ | $N_{\text{Htot}}$ $(10^{22} \text{ cm}^{-2})$ | $\Gamma_X$ | $P_X$ $(\text{erg s}^{-1} \text{ cm}^{-2})$ |
|---------|---------|--------|-------|-----------------|--------------|----------------------------------|----------------------------------|----------|----------------------------------|
| 050509B | CXO     | Burrows| 5588  | 2.3             | 49.1         | 0.016                                           | ...                              | ...      | $<4.5 \times 10^{-15}$             |
| 050709  | CXO     | Frail  | 5587  | 2.5             | 43.0         | 0.002                                           | ...                              | 2.35     | $9.0 \times 10^{-15}$             |
| 050724A | CXO     | Burrows| 6354  | 16.0            | 18.0         | 0.012                                           | ...                              | 2.35     | $5.2 \times 10^{-15}$             |
| 051221A | CXO     | Burrows| 6293  | 2.6             | 49.3         | 0.277                                           | 1.52                              | 1.89     | $4.8 \times 10^{-14}$             |
| 100117A | XMM     | Schurte| 56010 | 1.8             | 37.8         | 0.029                                           | 0.56                              | 2.70     | $6.9 \times 10^{-15}$             |
| 101219A | CXO     | Berger | 11106 | 4.1             | 19.8         | 0.058                                           | 0.80                              | 1.46     | $1.7 \times 10^{-14}$             |
| 110112A | CXO     | La Palombara | 14548 | 856            | 4.1           | 0.068                                           | 0.09                              | 2.30     | $3.7 \times 10^{-14}$             |
| 111020A | CXO     | Berger | 12543 | 3.0             | 19.7         | 0.143                                           | 0.90                              | 2.03     | $5.4 \times 10^{-15}$             |
| 111117A | XMM     | Schurte| 12544 | 10.2            | 19.8         | 0.143                                           | 0.90                              | 2.03     | $1.6 \times 10^{-14}$             |
| 120804A | XMM     | Schurte| 18176 | 1.9             | 23.3         | 0.267                                           | 0.26                              | 2.03     | $2.0 \times 10^{-14}$             |
| 130603B | XMM     | Fong   | 27257 | 7.0             | 6.9          | 0.327                                           | 0.16                              | 2.51     | $2.0 \times 10^{-14}$             |
| 140903A | CXO     | Sakamoto | 22500 | 23.6           | 3.7           | 0.141                                           | 0.05                              | 2.55     | $2.0 \times 10^{-15}$             |
| 140930B | CXO     | Fong | 15807 | 4.2             | 23.4         | 0.035                                           | ...                              | 2.24     | $4.6 \times 10^{-15}$             |
| 150101B | CXO     | Levan  | 15808 | 22.9            | 34.3         | 0.035                                           | ...                              | 1.64     | $3.8 \times 10^{-15}$             |
| 150109B | CXO     | Levan  | 15786 | 7.9             | 14.9         | 0.035                                           | ...                              | 2.95     | $3.0 \times 10^{-15}$             |
| 160624A | XMM     | Tanvir | 16082 | 3.9             | 27.4         | 0.058                                           | ...                              | 2.12     | $3.0 \times 10^{-15}$             |
| 170722B | XMM     | Fong | 17082 | 5.9             | 28.5         | 0.058                                           | ...                              | 2.22     | $2.8 \times 10^{-15}$             |
| 180418A | CXO     | Fong | 20180 | 7.7             | 24.1         | 0.010                                           | ...                              | 1.15     | $1.5 \times 10^{-13}$             |
| 191031D | CXO     | Fong | 20181 | 19.3            | 9.8          | 0.010                                           | ...                              | 2.66     | $2.6 \times 10^{-14}$             |
| 201006A | CXO     | Fong | 20192 | 38.5            | 27.6         | 0.010                                           | ...                              | 2.66     | $2.6 \times 10^{-14}$             |
| 210726A | CXO     | Fong | 22102 | 3.0             | 24.6         | 0.017                                           | ...                              | 1.71     | $5.7 \times 10^{-14}$             |
| 211106A | CXO     | Fong | 22104 | 3.4             | 24.6         | 0.017                                           | ...                              | 1.71     | $5.7 \times 10^{-14}$             |
| 211106A | CXO     | Fong | 22105 | 3.4             | 24.6         | 0.017                                           | ...                              | 1.71     | $5.7 \times 10^{-14}$             |
| 013009B | CXO     | Fong | 23543 | 10.5            | 19.8         | 0.011                                           | 0.21                              | 1.92     | $3.7 \times 10^{-14}$             |
| 013009B | CXO     | Fong | 08628 | 14.9            | 20.3         | 0.011                                           | 0.24                              | 1.92     | $2.0 \times 10^{-14}$             |

**Notes.** Column (1): GRB name. Column (2): observatory that obtained the observation. Columns (3)-(4): principal investigator (PI) of the program and identification number of the observation (obsID), respectively. Column (5): elapsed time between the burst trigger and the log-centered time of the observation (\(\delta\)). Column (6): final exposure time after filtering background events. Columns (7)-(8): Galactic column density, \(N_{\text{Htot}}\), and intrinsic absorption value, \(N_{\text{Htot}}\), respectively. The symbol \(\sim\) means that the contribution of \(N_{\text{Htot}}\) is negligible and is set to 0 in our fits. Column (9): X-ray photon index (\(\Gamma_X\)). The spectral parameter \(\Gamma_X\) is calculated in the 0.5–7 keV energy range for Chandra and between 0.3 and 10 keV for XMM-Newton (when information from both observatories is available, then a 0.5–7 keV energy range is applied). For observations with a joint spectral analysis, only the first value of \(\Gamma_X\) is shown with uncertainties, while for the rest of observations just the value of \(\Gamma_X\) is stated. Column (10): 0.3–10 keV unabsorbed X-ray fluxes (\(P_X\)). Errors are 1σ for measurements, whereas \(P_X\) upper limits are 3σ.

* Fixed spectral values to Swift spectral parameters.
* Fixed values to previous Chandra or XMM-Newton spectral parameters.
* Tied spectral parameters to perform joint spectral fitting between X-ray observations.
from 20″ radius circular regions centered on the XMM-Newton positions\textsuperscript{24} in the 0.3–10 keV energy band. To obtain the background count rate and spectral information for each detection, we used a source-free region with a size identical to the source region, randomly placed on the same detector quadrant as the afterglow. We verified that none of the data were affected by pileup. We generated rmf and arf files by running RMFGEN and ARFGEN, respectively. When available, we jointly fit the EPIC/pn and EPIC/MOS spectra of each SGRB (see Section 3.4). If X-ray afterglows were not detected, we obtained 3σ upper limits on the count rates (0.3–10 keV) fixed at the positions of the Swift/XRT afterglows using the same size of the XMM-Newton detection regions utilizing the EUPPER SAS task.

### 3.3. Swift Observations

For the Swift/XRT data, we collected all of the available X-ray afterglow information from the Swift light-curve repository\textsuperscript{25} (Evans et al. 2007, 2009). We obtained the unabsorbed X-ray flux light curves by applying the relevant counts-to-unabsorbed flux conversion factors to the count-rate light curves, depending on the Swift observing mode (i.e., the windowed timing (WT) and photon counting (PC) modes). The automatic spectral fitting routine fits each burst’s X-ray spectrum with a double-component absorbed power-law model with one of the absorption components set to the Galactic column density in the direction of the burst (\(N_{\text{H,\text{Gal}}}\); Willingale et al. 2013), and the other accounting for any excess in the line of sight as an intrinsic neutral hydrogen absorption column (\(N_{\text{H,int}}\)), while the power-law component is characterized by the X-ray photon index (\(\Gamma\)).

For the four cases (GRBs 130603B, 180418A, 200522A, and 210726A) in which the contaminating sources were discovered in Chandra observations (Section 3.1), we utilized the option “create time-sliced spectra” in the Swift repository to obtain the spectra of each bin in the dynamically\textsuperscript{26} binned XRT light curves. Performing a spectral analysis in which we account for the contamination of these unrelated astrophysical sources leads to lower SGRB afterglow fluxes at the tail of the XRT monitoring. In Section 3.4, we describe the method used to obtain the corrected unabsorbed X-ray flux light curves for each SGRB.

### 3.4. X-Ray Spectral Analysis

We analyzed all of the X-ray afterglow spectra of the 29 SGRBs in our sample utilizing \textsc{xspec} (12.10.1f; Arnaud 1996). Before proceeding with the spectral analysis, we binned the spectra with GRPPHA to guarantee at least one count per bin to avoid negative counts when accounting for the background during the analysis. For modeling the X-ray afterglow spectra in \textsc{xspec}, we used WILM abundances (Wilms et al. 2000) with X-ray cross sections set to \textsc{vern} (Verner et al. 1996) and statistics to \textsc{w}-statistics (Cash-statistics for Poisson data and background; Wachter et al. 1979). We characterized the spectra with a two-component absorption power-law model (\texttt{tbabs*ztbabs*pow}) defined by \(N_{\text{H,int}}\) (Willingale et al. 2013), \(N_{\text{H,int}}\) at the redshifts\textsuperscript{27} of the SGRBs when available (see Table 1), and \(\Gamma\).

Initially, we allowed all spectral parameters to vary as free except for \(N_{\text{H,int}}\) and \(z\). However, we find that for 14 bursts, the 3σ confidence interval of \(N_{\text{H,int}}\) was consistent with zero. Thus, we performed a revised spectral fit for these events setting \(N_{\text{H,int}} = 0\) (see Table 2). For SGRBs initially monitored by XRT and with more than one detection with Chandra or XMM-Newton, we performed a joint spectral fit of the entire data set tying \(\Gamma\) and \(N_{\text{H,int}}\) between spectra and leaving the normalization as a free parameter, which is valid because we did not find evidence for spectral evolution for any of the bursts. We determined the best-fit spectral parameters within the 0.5–7 keV and 0.3–10 keV energy ranges for the Chandra and XMM-Newton spectra, respectively.

For the SGRB afterglows that were detected by both XMM-Newton and Chandra, we set a common energy range of 0.5–7 keV, which is well covered by both observatories, and used a constant multiplicative model (\texttt{const*tbabs*ztbabs*pow}) to account for the cross-calibration between the different instruments of the observatories in our joint fitting. We set the XMM-Newton/EPIC-PN constant value to 1 and calculated the rest of the constants (\texttt{const*epic–mos1 = 1.088, const*epic–mos2 = 1.106, const*acis–s3 = 1.106, and const*xrt–pc = 0.965}) following Table 5 in Plucinsky et al. (2017).

Finally, we determined the unabsorbed X-ray fluxes (\(F_{\chi}\)) of the afterglows within the 0.3–10 keV energy range, fixing the spectral parameters to the best-fit values and using the \texttt{cflux} convolution model (\texttt{const*tbabs*ztbabs*cflux*pow}) in \textsc{xspec}. The unabsorbed X-ray fluxes (0.3–10 keV), together with best-fit parameters and their 1σ uncertainties are listed in Table 2. We calculated the 3σ X-ray unabsorbed flux upper limits from the upper limits of the count rates, using the \textsc{heasarc} \textsc{webpimms} tool\textsuperscript{28} with the best-fit spectral parameters available from previous afterglow detections for each case. The 3σ upper limits for the X-ray unabsorbed fluxes are listed in Table 2.

There are four cases with contaminating sources (XI) in the Swift/XRT or XMM-Newton source regions that are resolved in the Chandra observations. We employed a single absorbed power-law model (\texttt{tbabs*pow}) to characterize their Chandra spectra. Then we took into account these spectral parameters in the Swift and XMM-Newton spectral modeling of the SGRB afterglows and calculated the unabsorbed X-ray flux from the afterglow in the 0.3–10 keV energy band (following the same method as described in Rouco Escorial et al. 2021). For that, we set \texttt{cflux} to account only for the afterglow (AG) spectral component of the model: \(\texttt{tbabs*tbabs*cflux*pow}_{\text{AG}}\) (\texttt{tbabs*pow})\textsubscript{X1}.

### 4. Inferred Properties from Broadband Modeling

Here we model the broadband afterglows of our sample considering the standard synchrotron forward shock model (Sari et al. 1998; Granot & Sari 2002). In this scenario, the afterglow shock originates from the interaction of a relativistic blast wave with a constant-density medium, which is the expected environment for an NS merger (e.g., Paczynski 1986; Eichler et al. 1989). In what follows, we first determine the

\textsuperscript{24} For SGRBs with Chandra and XMM-Newton afterglow detections, we utilize the more precise Chandra position.
\textsuperscript{25} https://www.swift.ac.uk/xrt_curves/
\textsuperscript{26} For more information see https://www.swift.ac.uk/xrt_curves/docs.php#products.
\textsuperscript{27} If the distance to the SGRB was unknown, we set \(z = 0\).
\textsuperscript{28} https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl
temporal and spectral evolution, parameterized by $F_{\nu} \propto \nu^{\alpha} \nu^{\beta}$, where $\alpha$ and $\beta$ are the temporal and spectral power-law indices, respectively. We then use these indices and the closure relations given by the synchrotron model (Granot & Sari 2002) to determine the power-law index of the input distribution of accelerated electrons ($\rho$), providing a framework for determining the locations of the observing bands with respect to the three break frequencies of the synchrotron spectrum: the self-absorption frequency ($\nu_{\text{abs}}$), peak frequency ($\nu_{\text{m}}$), and cooling frequency ($\nu_{\text{c}}$). We then fit the available observational data using the mapping from Granot & Sari (2002) to determine each burst’s physical properties. These properties include the isotropic-equivalent energy of the jet ($E_{K,\text{iso}}$), the density of the circumburst environment ($n_0$), and the fractions of the postshock energy transmitted to electrons ($\epsilon_e$) and magnetic field ($\epsilon_B$). In Section 5, we apply these properties to determine the jet opening angles of the bursts.

4.1. X-Ray Temporal and Spectral Fitting

The temporal behavior of X-ray afterglows can be well described with a power law or a series of connected power laws (e.g., Zhang et al. 2006; Evans et al. 2007; Margutti et al. 2013). To ensure that we are only using data during the forward shock afterglow phase, we ignore all of the data at $\Delta t < 200$ s, which often includes high-latitude emission and the tail of the $\gamma$-ray emission (Zhang et al. 2006; Racusin et al. 2009; and reference therein). Additionally, during the fits we omit portions of the light curves that are clear deviations from the main power laws.

To remain agnostic to the particular best-fit model, we first fit every SGRB afterglow light curve using single, broken, and triple power-law models, described by Equations (A1), (A2), and (A3), respectively (see Appendix A for more details). The main parameters of our models are the series of temporal decay indices ($\alpha_{1,2,3}$), the flux normalization ($C$), the break times ($t_{b,1,2}$), and the smoothness parameters ($s_{1,2}$). For every fit, we set all model parameters as free, except for the smoothness indices which are set as constants in the broken and triple power-law models.

To perform the light-curve fitting, we use the Python EMCEE package (Foreman-Mackey et al. 2013) in which we apply an affine-invariant Markov Chain Monte Carlo (MCMC) ensemble sampler (Goodman & Weare 2010; Foreman-Mackey et al. 2019) to find the solution with the highest log-likelihood for each model together with the model parameters. We initiate each fit with 15,000 steps, each with 100 walkers, and discard the initial 500 steps as “burn in” when the average log-likelihood across the chains reaches a stable value. We then calculate the medians and 1σ credible regions from the posteriors for each parameter, and use these values to determine the reduced-$\chi^2$ value for each model.

Based on the results from our light-curve fitting procedure for each burst, we use the F-test to determine whether a simpler model provides a statistically better fit to our data than a more complex model. In effect, we first test the null hypothesis ($H_0$) that a single power-law model is sufficient to describe the X-ray afterglow light curve. If $H_0$ is not accepted, then we test a second null hypothesis ($H'_0$) that a broken power law is the best-fit model. If $H'_0$ is not accepted, the afterglow light curve is best described then by a triple power-law model (see Appendix B). We find that 12 SGRBs are best fit by a single power-law model, 11 by a broken power law, and 6 by a triple power-law model. The medians and 1σ uncertainties of the best-fit parameters for each SGRB are shown in Table 3. For afterglows best described by a single power law, we find a median of $\langle \alpha_X \rangle \approx 1.00$, which is in agreement with the weighted mean of $\alpha_X$ found by Fong et al. (2015a).

For SGRBs with light curves best described by the broken power-law model, we find two scenarios: (i) $\alpha_1 < \alpha_2$, in which the afterglow light curve transitions from a steep power law of $\alpha_1 \lesssim 1$ to a shallower power law of $\alpha_2 \approx \{-1.5, -0.3\}$, or (ii) $\alpha_1 > \alpha_2$, in which the afterglow light curve steepens. Cases in which $\alpha_2 \lesssim -2$ can be associated, in general, with jet breaks (Section 5).

For the triple power-law model, we identify a range of morphologies in terms of afterglow behavior. Similar to the broken power-law afterglows, bursts with their final segments following the condition, $\alpha_3 \lesssim -2$ can be viable jet breaks (see Section 5 for further criteria). We note that our analysis also uncovers several instances of shallow power-law segments of $\alpha_X \approx -0.6$, which have been proposed as phases related to an extra injection of energy, for example driven by a potential magnetar central engine (Rowlinson et al. 2013; Gompertz et al. 2014; Bernardini 2015; Liu et al. 2017; Stratta et al. 2018).

We also determine the X-ray spectral index ($\beta_X$) for each SGRB. We utilize the photon indices derived from our spectral analysis in Section 3, and the relation $\beta_X \equiv 1 - \Gamma_X$. We find that the value of $\beta_X$ varies between $-0.15$ and $-1.9$ depending on the individual cases shown in Table 3. Overall we find a weighted mean of $\langle \beta_X \rangle = -0.99 \pm 0.06$. This value is consistent within the errors with that reported by Fong et al. (2015a).

4.2. Isotropie-equivalent Kinetic Energies and Circumburst Densities

Here we constrain the values of $p$, $E_{K,\text{iso}}$, and $n_0$ as described in Section 4 using all available X-ray, optical, near-infrared, and radio data in the framework of the standard synchrotron forward shock model (Sari et al. 1998; Granot & Sari 2002); these are key parameters which feed into the determination of the opening angles. For the SGRBs detected during 2005–2015, we utilize the broadband analysis from Fong et al. (2015a) for the values of $p$, $E_{K,\text{iso}}$, and $n_0$. We also use the analysis of Schroeder & Margalit (2020) to determine these parameters for the particular cases of GRBs 050509B, 150424A, and 160821B, and the latest analysis of GRB 211106A from Laskar et al. (2022). For the remaining SGRBs discovered beyond 2015, we follow the methods of Fong et al. (2015a) to constrain these shock and environment parameters.

First, we constrain the position of $\nu_X$ with respect to $\nu_c$ (e.g., $\nu_X > \nu_c$ or $\nu_m < \nu_X < \nu_c$), assuming a constant-density medium. We determine under which scenario the values of $p$, independently determined from $\alpha_X$ and $\beta_X$, adhere to the closure relations given by Granot & Sari (2002). For each SGRB, we require that the values of $p$ derived from $\alpha_X$ and $\beta_X$ to be consistent within $1\sigma$, calculate the weighted mean

As an example, we do not include the data of GRB 050724A at $0.1 < \Delta t < 1.3$ days since its afterglow light curve shows a very clear X-ray flux enhancement on top of the main power-law decay trend (Campana et al. 2006; Grepe et al. 2006; Margutti et al. 2011).

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29 We note that the spectral parameters of SGRBs observed with Chandra are calculated within the 0.5–7 keV energy band (see Section 3.1). We assume that these spectral parameters, in particular $\Gamma_X$ and therefore $\beta_X$, are also applicable to the 0.3–10 keV energy range since most of the Chandra effective area is included in both energy ranges.
| Name      | Model | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\beta_X$ | $t_{\text{SI}}$ | $t_{\text{II}}$ |
|-----------|-------|------------|------------|------------|-----------|----------------|----------------|
| 050724A   | TPL   | $-4.91 \pm 0.12$ | $-0.80 \pm 0.04$ | $-2.91 \pm 1.15$ | $-0.52 \pm 0.15$ | 0.0078 $\pm 0.0004$ | 8.74 $\pm 1.26$ |
| 051221A   | TPL   | $-1.56 \pm 0.08$ | $-0.69 \pm 0.03$ | $-1.66 \pm 0.09$ | $-0.89 \pm 0.14$ | 0.012 $\pm 0.007$ | 1.29 $\pm 0.40$ |
| 110102A   | BPL   | $-0.80 \pm 0.38$ | $-1.23 \pm 0.35$ | ... | $-1.04 \pm 0.21$ | 2.747 $\pm 1.496$ | ... |
| 130063B   | BPL   | $-0.75 \pm 0.03$ | $-2.10 \pm 0.09$ | ... | $-1.51 \pm 0.57$ | 0.115 $\pm 0.013$ | ... |
| 140039A   | BPL   | $-1.05 \pm 0.07$ | $-1.04 \pm 0.13$ | $-2.32 \pm 0.37$ | $-1.24 \pm 0.47$ | 0.088 $\pm 0.473$ | 0.92 $\pm 0.87$ |
| 150424A   | SPL   | $-2.97 \pm 0.62$ | $-0.74 \pm 0.04$ | $-2.15 \pm 0.39$ | $-0.71 \pm 0.07$ | 0.0068 $\pm 0.7488$ | 1.56 $\pm 1.45$ |
| 160821B   | SPL   | $-4.33 \pm 0.23$ | $-0.44 \pm 0.25$ | $-2.16 \pm 0.75$ | $-1.23 \pm 0.15$ | 0.009 $\pm 0.002$ | 0.89 $\pm 1.14$ |
| 200411A   | BPL   | $-0.82 \pm 0.05$ | $-3.96 \pm 1.61$ | ... | $-0.72 \pm 0.22$ | 0.846 $\pm 0.413$ | ... |
| 200532A   | BPL   | $-0.67 \pm 0.06$ | $-1.74 \pm 0.41$ | $-0.67$ | $-0.38 \pm 0.20$ | 2.410 $\pm 1.601$ | ... |
| 211106A$^b$ | SPL   | $-0.97 \pm 0.03$ | ... | ... | $-0.92 \pm 0.30$ | ... | ... |

| Name      | Model | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\beta_X$ | $t_{\text{SI}}$ | $t_{\text{II}}$ |
|-----------|-------|------------|------------|------------|-----------|----------------|----------------|
| 050908B   | BPL   | $-0.91 \pm 0.15$ | ... | ... | $-0.50 \pm 0.08$ | ... | ... |
| 050709    | BPL   | $-2.75 \pm 1.94$ | $-0.35 \pm 0.22$ | ... | $-1.35 \pm 0.33$ | 2.571 $\pm 1.778$ | ... |
| 100117A   | BPL   | $-3.42 \pm 0.57$ | $-1.55 \pm 0.87$ | ... | $-1.70 \pm 0.35$ | 0.006 $\pm 0.004$ | ... |
| 10129A    | SPL   | $-1.41 \pm 0.13$ | ... | ... | $-0.46 \pm 0.24$ | ... | ... |
| 11012A    | SPL   | $-1.04 \pm 0.05$ | ... | ... | $-1.30 \pm 0.04$ | ... | ... |
| 11117A    | SPL   | $-1.28 \pm 0.06$ | ... | ... | $-0.56 \pm 1.42$ | ... | ... |
| 120804A   | SPL   | $-1.06 \pm 0.01$ | ... | ... | $-0.75 \pm 0.11$ | ... | ... |
| 140930B   | SPL   | $-2.07 \pm 0.22$ | $-1.26 \pm 0.06$ | ... | $-0.64 \pm 0.08$ | 0.011 $\pm 0.008$ | ... |
| 150101B   | SPL   | $-0.91 \pm 0.10$ | ... | ... | $-1.95 \pm 0.13$ | ... | ... |
| 150423A   | SPL   | $-0.99 \pm 0.05$ | ... | ... | $-0.47 \pm 0.08$ | ... | ... |
| 150831A   | TPL   | $-0.62 \pm 0.42$ | $-5.82 \pm 0.21$ | $-1.07 \pm 0.06$ | $-0.88 \pm 0.50$ | 0.0018 $\pm 0.0001$ | 0.0035 $\pm 0.0001$ |
| 160624A   | BPL   | $-0.66 \pm 0.93$ | $-3.07 \pm 0.64$ | ... | $-0.60 \pm 0.40$ | 0.0015 $\pm 0.0001$ | ... |
| 170728B   | BPL   | $-0.63 \pm 0.06$ | $-1.32 \pm 0.03$ | ... | $-0.15 \pm 0.23$ | 0.034 $\pm 0.006$ | ... |
| 180418A   | BPL   | $-0.98 \pm 0.14$ | ... | ... | $-0.85 \pm 0.14$ | ... | ... |
| 180727A   | BPL   | $-1.95 \pm 1.02$ | $-0.67 \pm 0.09$ | $-1.22 \pm 0.21$ | $-0.61 \pm 0.35$ | 0.019 $\pm 0.015$ | ... |
| 191031D   | SPL   | $-2.55 \pm 0.25$ | $-0.67 \pm 0.14$ | ... | $-0.93 \pm 0.28$ | ... | ... |
| 200219A   | BPL   | $-5.66 \pm 0.25$ | $-1.34 \pm 0.14$ | $-0.18$ | $-0.83 \pm 0.39$ | 0.0062 $\pm 0.0029$ | ... |
| 210066A   | SPL   | $-1.01 \pm 0.07$ | ... | ... | $-1.10 \pm 0.55$ | ... | ... |
| 210726A   | SPL   | $-0.72 \pm 0.02$ | ... | ... | $-0.71 \pm 0.11$ | ... | ... |

Notes. (Column 1): GRB name. (Column 2): best-fit model for the X-ray afterglow. The abbreviations “SPL,” “BPL,” and “TPL” represent the single, broken, and triple power-law models, respectively. (Column 3)–(5): temporal decay indices for each segment of the best-fit model. Column (6): X-ray spectral index. (Columns (7)–(8): time (in days) of the breaks for the BPL and TPL models, respectively. In the case of SGRBs with detected jet breaks in their light curves, we identify the time of the jet break (Section 5) with $t_{\text{SI}}$ for the broken power-law model and $t_{\text{II}}$ for the triple power-law model. Errors are 1σ.

$^a$Value derived from Swift photon index ($\gamma_X$).

$^b$The radio afterglow light curve of GRB 211106A shows a jet break at $t_j \approx 29$ days (Laskar et al. 2022).
parameters is based on results from GRB afterglow fitting (Ryan et al. 2015; Beniamini & van der Horst 2017) and theoretical studies which show that part (typically ~10%) of the kinetic energy may be deposited into nonthermal particles (Spitkovsky 2008). For these cases, we need lower values of $e_B = 10^{-4} - 0.01$ in order to find $E_{K,iso}$ and $n_0$ solution pairs (e.g., Panaitescu & Kumar 2002; Sironi & Spitkovsky 2011). In particular, these cases are GRBs 150424A, 160821B (Schroeder & Margalit 2020), 191031D, 200219A, and 200522A (Fong et al. 2021) with $e_B < 0.01$, GRB 140903A with $e_B = 10^{-3}$ (Fong et al. 2015a), GRB 050724A with $e_B = 10^{-4}$ (Fong et al. 2015a), and GRB 211106A with $e_B = 10^{-5}$ (assuming $z = 1$ and IC/KN corrections; Laskar et al. 2022). Additionally, we set the redshift to the median value of $z = 0.64$ (Nugent et al. 2022) for SGRBs with no redshift information (GRBs 110112A and 201006A; Table 1). We point out that the derived physical parameters will be degenerate with respect to the fraction of particles accelerated into a nonthermal distribution (Eichler & Waxman 2005).

To calculate the distributions of $E_{K,iso}$ and $n_0$, we consider a parameter space with 1000 logarithmically spaced steps for each parameter, with ranges of $E_{K,iso} = 10^{46} - 10^{46}$ erg and $n_0 = 10^{-6} - 10^3$ cm$^{-3}$, where $n_{min} = 10^{-6}$ cm$^{-3}$ corresponds to the typical value of the intergalactic medium. We then constrain the $E_{K,iso}$ and $n_0$ parameter space by combining the probability distributions from each wavelength for each SGRB, marginalize over each parameter, and normalize the 1D distributions. In Table 4 we report the values of $E_{K,iso}$ and $n_0$ (1σ uncertainties), which vary between $[3 \times 10^{50}, 1.7 \times 10^{53}]$ erg and $[0.7 \times 10^{-5}, 0.7]$ cm$^{-2}$, respectively. The median values for the final sample of 29 SGRBs are $(E_{K,iso}) \approx 4.0 \times 10^{51}$ erg and $(n_0) \approx 6.4 \times 10^{-4}$ cm$^{-3}$ considering the equipartition parameters in Table 4.

5. Jet Opening Angles, Beaming-corrected Energetics, and Event Rates

As a consequence of relativistic beaming, the observed temporal behavior of a spherical expansion for an on-axis observer is initially similar to that of a highly collimated relativistic outflow. As the jet interacts with the circumburst medium, the value of its bulk Lorentz factor ($\Gamma$) declines over time to reach a value equal to the inverse of the jet opening angle ($\Gamma \sim \theta^{-1}$; Piran 1995) and consequently the edge of the highly collimated relativistic outflow becomes visible to the observer. This moment is known as the time of the jet break ($t_j$) and observationally manifests as an achromatic and temporal steepening in the afterglow light curve (Sari et al. 1999; van Eerten & MacFadyen 2013), after which the outflow may follow lateral expansion (Granot & Piran 2012). At this point, the jet undergoes a lateral expansion and the afterglow decline rate can be analytically described by $t^{-0.8}$ (Rhoads 1999; Sari et al. 1999). By constraining the parameter $t_j$ in the SGRB afterglow light curves, one can additionally derive $\theta_j$.

5.1. Determination of the Jet Opening Angles

To identify jet breaks from the best-fit models, we define a jet break as the time when $\alpha$ significantly steepens. Quantitatively, for $\alpha_X > \alpha_{X+1}$ (i.e., for those curves showing a steepening), we classify light curves as having jet breaks if they exhibit: (i) $\alpha_{X+1} < -1.75$, and (ii) $0.75 < |\Delta \alpha_X| < 3$. For instance, considering an ISM-like medium for the closure relations given by Granot & Sari (2002) and assuming $2 < p < 3$ (Fong et al. 2015a), we know that $\alpha_X$ can range between $-1.5 < \alpha_X < -0.75$ if $\nu_X < \nu_c$ and $-1.75 < \alpha_X < -1.0$ if $\nu_c < \nu_X$, in case of a spherical outflow. Therefore, if the post-break segment of a light curve is steeper than $\alpha_X = -1.75$, the only real justification is a jet break instead of the transition of $\nu_c$ across the X-ray band. Additionally, the transition of $\nu_c$ across the X-ray band predicts a maximum value of the change in slope of $|\Delta \alpha_X| = 0.25$ (Sari et al. 1998), so that any larger $\Delta \alpha$ is most naturally explained by a jet break. Considering an interstellar medium (ISM) and a top-hat geometry for cosmological SGRB jets with the observer along the jet axis,$^{52}$ we combine the information from the X-ray afterglow light curves with constraints on $E_{K,iso}$ and $n_0$ (Section 4) to calculate $\theta_j$ or their lower limits. We use the following equation given by Sari et al. (1999) and Frail et al. (2001):

$$\theta_j = 9.5 t_j^{3/8} (1 + z)^{-3/8} E_{K,iso,52}^{-1/8} n_0^{1/8} \text{[deg]}.$$  \hspace{1cm} (2)

where $t_j$ is time in days, $E_{K,iso,52}$ is in units of $10^{52}$ erg, and $n_0$ is in units of cm$^{-3}$. For bursts with detected jet breaks we set $t_j$ to the best-fit time of the break in our calculation of $\theta_j$ (Table 3). In the case of SGRBs with no detected jet breaks (e.g., well described by single power-law declines), we fix $t_j$ to the time of the last X-ray detection (considering this time as a lower limit on $t_j$) to obtain lower limits on the jet opening angles.

5.2. Distribution of SGRB Jet Opening Measurements

Using the aforementioned criteria, we find that nine SGRBs (050724A, 051221A, 111020A, 130603B, 140903A, 150424A, 160821B, 200411A, and 200522A; Table 3) exhibit temporal steepenings in their X-ray afterglow light curves that we attribute to jet breaks. We also add to this group the case of GRB 211106A, for which the jet break was uncovered in the radio afterglow light curve (Laskar et al. 2022). Thus, our final subsample is composed of 10 SGRBs with jet breaks (Figure 2). We confirm the existence of the jet breaks for eight cases that have been already published: GRB 051221A (Burrows et al. 2006; Soderberg et al. 2006), GRB 111020A (Fong et al. 2012), GRB 130603B (Fong et al. 2014), 140903A (Troja et al. 2016), GRB 150424A (Jin et al. 2018), GRB 160821B (Lamb et al. 2019; Troja et al. 2019), GRB 200522A (O’Connor et al. 2021), and GRB 211106A (Laskar et al. 2022). However, we update the time of the jet breaks in the X-ray afterglow light curves for all these cases based on our uniform modeling (see Table 4), except the jet-break time of GRB 211106A, which was detected in the radio band. Additionally, we report on two new jet-break detections in X-rays that have not been found to date: GRBs 050724A and 200411A (see Table 4). For these 10 SGRBs, we find that their median jet-break times span a range of $t_j \approx 0.1$–30 days. We use the posteriors of $t_j$ for each case to build the total probability distribution of jet-break times.

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$^{52}$ One of the lessons learned from GRB 170817A is that jets can be more complex and structured. Wu & MacFadyen (2019) showed that cosmological SGRBs share a similar jet structure to GRB 170817A. Indeed, plateau-like features in early X-ray afterglow light curves may be explained if structured jets are observed slightly beyond the GRB jet’s core (Beniamini et al. 2020), or from high-latitude emission of a structured jet (Oganesyan et al. 2020). Likewise, Urrutia et al. (2021) demonstrated that structured jets can have significantly more injected energy at large observing angles than top-hat jets. However, for our SGRB sample, the emission is completely dominated by the jet core, making the detection of any structure difficult. Therefore, the assumption of an SGRB top-hat jet geometry is a reasonable approximation for our study.
| GRB    | $\nu_c < \nu_t$ | $p$  | $\epsilon_B$ | $E_{\nu_{\text{iso}}}$ (erg) | $\langle E_{\nu_{\text{iso}}} \rangle$ (erg) | $(\langle n_b \rangle)$ (cm$^{-3}$) | $\langle \theta_i \rangle$ or $\langle \theta_{b,\text{min}} \rangle$ (deg) | $f_b$ | $E_e$ (erg) | $E_K$ (erg) | $\eta_c$ |
|--------|----------------|------|--------------|-------------------------------|---------------------------------|---------------------------------|---------------------------------|---|------------|------------|------|
|        |                |      |              |                               |                                 |                                 |                                 |   |            |            |      |
| 050724A| N              | 2.29| $\pm 0.10$  | $10^{-4}$                     | $(1.2 \pm 0.2) \times 10^{51}$ | $(6.9 \pm 5.9) \times 10^{49}$ | $0.20 \pm 0.03$                    | 3.05 | $10^{54}$  | $10^{56}$  | 0.40 |
| 051211A| Y              | 2.24| $\pm 0.07$  | 0.1                          | $(8.6 \pm 5.4) \times 10^{50}$ | $(4.2 \pm 5.4) \times 10^{41}$ | $0.20 \pm 0.03$                    | 0.74 | $10^{56}$  | $10^{57}$  | 0.76 |
| 111020A| Y              | 2.08| $\pm 0.32$  | 0.1                          | $(3.9 \pm 0.2) \times 10^{50}$ | $(4.6 \pm 1.4) \times 10^{42}$ | $0.07 \pm 0.03$                    | 1.0  | $10^{56}$  | $10^{56}$  | 0.08 |
| 130603B| Y              | 2.70| $\pm 0.06$  | $10^{-3}$                     | $(2.9 \pm 0.2) \times 10^{51}$ | $(0.3 \pm 0.3) \times 10^{-2}$ | $0.20 \pm 0.03$                    | 0.71 | $10^{56}$  | $10^{57}$  | 0.73 |
| 140903N| N              | 2.27| $\pm 0.16$  | $10^{-3}$                     | $(2.9 \pm 0.3) \times 10^{50}$ | $(4.6 \pm 1.4) \times 10^{-2}$ | $0.10 \pm 0.03$                    | 1.0  | $10^{56}$  | $10^{57}$  | 0.10 |
| 150424A| Y              | 2.40| $\pm 0.15$  | 0.01                          | $(3.7 \pm 0.6) \times 10^{51}$ | $(2.0 \pm 0.6) \times 10^{52}$ | $0.10 \pm 0.03$                    | 0.71 | $10^{56}$  | $10^{57}$  | 0.52 |
| 160821B| Y              | 2.36| $\pm 0.14$  | $10^{-4}$                     | $(3.3 \pm 0.3) \times 10^{50}$ | $(4.8 \pm 0.9) \times 10^{52}$ | $0.10 \pm 0.03$                    | 0.71 | $10^{56}$  | $10^{57}$  | 0.18 |
| 200411A| Y              | 2.10| $\pm 0.07$  | 0.1                          | $(2.0 \pm 0.3) \times 10^{50}$ | $(3.7 \pm 0.5) \times 10^{52}$ | $0.10 \pm 0.03$                    | 0.71 | $10^{56}$  | $10^{57}$  | 0.08 |
| 200522A| Y              | 1.78| $\pm 0.30$  | 0.01                          | $(4.9 \pm 0.2) \times 10^{50}$ | $(3.0 \pm 0.3) \times 10^{51}$ | $0.10 \pm 0.03$                    | 0.71 | $10^{56}$  | $10^{57}$  | 0.10 |
| 211060A| N              | 2.47| $\pm 0.05$  | $10^{-5}$                     | $(4.4 \pm 0.4) \times 10^{51}$ | $(1.0 \pm 0.2) \times 10^{53}$ | $0.10 \pm 0.03$                    | 0.71 | $10^{56}$  | $10^{57}$  | 0.03 |

**Notes.** Column (1): GRB name. Column (2): "Y" (yes) and "N" (no) indicate whether not $\nu_c$ is above $\nu_K$. Column (3): power-law index of the input distribution of accelerated electron. Column (4): postshock energy fractions transmitted to the magnetic field ($\epsilon_B$). Column (5): the isotropic $\gamma$-ray energy ($E_{\nu_{\text{iso}}}$) values. Column (6): the median values of the isotropic kinetic energy ($\langle E_{\nu_{\text{iso}}}, \rangle$). Column (7): the median values of the circumburst density ($\langle \rho \rangle$). Column (8): median values of the jet opening angles detections and lower limits represented by $\theta_i$ and $\theta_{b,\text{min}}$. Column (9): the beaming correction factor ($f_b$). Column (10): true beaming-corrected $\gamma$-ray energy (erg). Column (11): true beaming-corrected kinetic energy (erg). Column (12): $\gamma$-ray efficiency ($\eta_c$) calculated as $\eta_c = E_e/(E_{\nu_{\text{iso}}} + E_K)$. We use $E_e = 3 \times \gamma_{\text{iso}} \times d_2^2 (1 + z)^{-1}$, where $\gamma_{\text{iso}}$ is the bolometric correction factor to convert the Swift/BAT fluence ($f_e$) in the 15–150 keV energy band to the 1–10,000 keV energy band ($\gamma_{\text{iso}} = 5$), and $d_2$ is the luminosity distance (for SGRBs with unknown redshifts in Table 1 we assign the fiducial value of $z = 0.6$; Nugent et al. 2022). The isotropic kinetic energy and circumburst density are calculated with the fraction of the postshock energy transmitted to electrons ($\epsilon_e$) fixed to 0.1 for the different values of $\epsilon_B$ and redshifts (Table 1). We define $f_e$ as $f_e = 1 - \cos(\beta)$. Uncertainties are 1σ.

$^a$ The $E_{\nu_{\text{iso}}}$ value of GRBs 050709 is given in the 1–10,000 keV energy band by Villasenor et al. (2005).

$^b$ Values obtained from the analysis of Laskar et al. (2022) considering $z = 1$ and IC/KN corrections.
detected jet breaks (Figure 4, left). The median and 1σ confidence intervals for each jet measurement are reported in Table 4.

We find that the angles for GRBs 051221A, 111020A, 140903A, 160821B, and 200522A are in agreement within the errors with those reported by Burrows et al. (2006), Soderberg et al. (2006), Fong et al. (2012), Troja et al. (2019), and O’Connor et al. (2021), respectively. However, we find an opening angle of ∼3° for GRB 140903A, narrower than θj ≈ 5° (Troja et al. 2016), and a narrower opening angle measurement of ∼0° for GRB 150424A instead of θj ∼ 7° (Jin et al. 2018). For GRB 050724A, we now measure an opening angle of θj ≈ 34°, which is consistent with the previous wide opening angle lower limit of θj ≥ 25° (Grupe et al. 2009). The detection of a new jet break here is driven by the last Chandra detection at δt = 21.6 days for which we find an ∼0.8 times fainter flux (see Table 2) than that reported by Grupe et al. (2006). This measurement is a limiting case of the jet opening angle since theoretical studies of postmerger outflows derive a maximum value of θj,max ≈ 30° (Ruffert & Janka 1999; Aloy et al. 2005; Rosswog 2005; Rezzolla et al. 2011; Lazzati et al. 2021).

In the case of GRB 130603B, Fong et al. (2014) found a jet break at δt ≈ 0.47 days in the optical and radio afterglow light curves, but not in the X-ray band. However, our new MCMC modeling shows a jet break at ≈0.11 days posttrigger in the X-ray light curve. This earlier jet-break time is driven by the correction of the contribution of the X-ray contaminant (Appendix C) to the afterglow light curve. Therefore, one does not need to invoke extra energy injection from a magnetar to explain the X-ray flux level of late-time observations. We constrain the opening angle measurement of GRB 130603B to θj ≈ 4°, which is in agreement with the lower end of the opening angle range (∼4°–8°) for this event reported by Fong et al. (2014). For the jet opening angle measurements, overall, we find a median value of ⟨θj,det⟩ = 6°[−3°2, +9°3] for bursts with jet opening angle measurements, which is consistent with previous studies (Fong et al. 2015a; Jin et al. 2018) and in line with the opening angle estimates of jets for SGRBs produced by BNS mergers (Ghirlanda et al. 2016). In the case of SGRB 170817A, the first bona fide detection of an SGRB jet launched by a BNS merger, the range of values inferred for the core is θj,core = 2°–4° (Margutti & Chornock 2021), which is narrower than the median value we find for the SGRB jet opening angle measurements. It is clear from Figure 4 (right) that the probability beyond θj ≳ 15° is dominated by two events, GRBs 050724A and 211106A.

5.3. Distribution of Jet Lower Limits: A Population of Wider Jets

We also build probability distributions for the 19 SGRBs with inferred lower limits on the opening angles. We again perform 5000 random draws from the correlated distributions of EK,iso and n0. For these cases, we instead fix the jet-break time to the (log-centered) time of the last X-ray detection. Using Equation (2), we obtain the posterior distribution of the opening angle lower limit for each event, and report the median value of the minimum opening angle and 1σ confidence intervals (Table 4). We find that the range of minimum opening angles varies between θj,min ≈ 0°–3–26°.

We find that the minimum opening angles of six events (SGRBs 050709, 100117A, 111117A, 120804A, 150101B, and 180418A) are ≥1σ larger than ⟨θj,1st⟩, indicative of a population

Figure 2. 0.3–10 keV unabsorbed X-ray flux light curves of SGRBs with detected jet breaks. All SGRBs are color coded with their corresponding best-fit models (solid lines). Symbols indicate each set of observations obtained by the different observatories or observing modes (top legend). In addition, we note that the afterglow light curve of GRB 211106A exhibits evidence for a jet in the radio band; however it is wide enough to elude detection in the X-rays. Triangles indicate 3σ upper limits. Vertical lines from the top show the times of the jet breaks for each SGRB. Calculated uncertainties correspond to 1σ.
of wider jets. To investigate if the distribution of lower limits is statistically distinct from the distribution of jet measurements, we compare the CDFs at their 68% credible regions. If the median of each distribution lies within the other we expect the true event rate to be larger by a factor of \( f_\text{det}^{-1} \), where \( f_\text{true} = f_\text{det}^{-1} f_\text{obs} \).

For the SGRBs with opening angle measurements in our sample, we build the CDF of \( f_\text{det} \) by calculating the beaming correction factors using every value that composes the distribution of opening angles (Section 5.2). We find a median of \( (f_\text{det})_{\text{med}} = 0.6[-0.4, +3.0] \times 10^{-2} \) for the 10 bursts with well-measured opening angles. This value is consistent within the errors with that quoted in Fong et al. (2015a). The \( f_\text{det} \) value is essentially a minimum value on the median beaming correction factor as the sample used to derive it comprises jet measurements which likely represent the narrowest jets. For the mock sample including wide jets, the median value expectedly shifts to a larger value of \( (f_\text{det})_{\text{med}} = 1.2[-1.0, +2.5] \times 10^{-2} \).

Using bursts with opening angle measurements, we find population median isotropic-equivalent kinetic and \( \gamma \)-ray energies of \( \langle E_{\text{K,iso}} \rangle \approx 4.0 \times 10^{51} \) erg and \( \langle E_{\gamma,\text{iso}} \rangle \approx 1.6 \times 10^{51} \) erg (1–10,000 keV), respectively, with a \( \gamma \)-ray efficiency of \( \langle \eta_\gamma \rangle \approx 0.14 \). Incorporating \( (f_\text{det})_{\text{med}} \), we obtain median beaming-corrected kinetic and \( \gamma \)-ray energies of \( (E_\text{K}) \approx 2.3 \times 10^{50} \) erg and \( (E_\gamma) \approx 4.9 \times 10^{48} \) erg, respectively. This results in a total beaming-corrected energy of \( (E_{\text{true,iso}}) \equiv (E_\text{K}) + (E_\gamma) \approx 2.8 \times 10^{49} \) erg. If we assume similar isotropic-equivalent kinetic and \( \gamma \)-ray energies for the mock sample including wide jets, the median total beaming-corrected energy of the SGRB population increases to \( (E_{\text{true,iso}}) \approx 1.9 \times 10^{50} \) erg. These values are similar to the energy scales found in previous works where \( E_\text{K} \approx 10^{49} \) erg and \( E_{\text{true,iso}} \approx 10^{48} \) erg (Berger 2014; Fong et al. 2015a; Jin et al. 2018). In addition, even though the jet core of GRB 170817A is more collimated than most of our SGRB measurements, its total inferred energetics are similar with \( E_\text{K} \approx 10^{49} \)–\( 10^{51} \) erg (Margutti & Chornock 2021).

Figure 3. Distribution of the jet-break times for 10 SGRBs with jet-break detections (gray histogram) derived from the individual jet-break time posteriors. The gray arrow indicates the median jet-break time of \( t_j = 1.5[-1.2, +7.7] \) days. The distribution at \( t_j > 20 \) days is clearly dominated by a peak which represents the late-time detection of the GRB 211106A jet break in the radio band. For the 19 lower limits, the times of the last X-ray detections are indicated with color-coded lower limits, which roughly correspond to the time out to which we are sensitive to jet breaks for each event. A significant fraction (10/19) of the lower limits are found at times of \( t_j > t_j \), and specifically there are six events with final X-ray detections at \( t_j > 10 \) days. This shows the existence of an SGRB group with jet breaks located at very late times (and potential wide opening angles), as in the case of GRB 211106A.

5.4. Energy Scale and Event Rate

The jet opening angle distribution affects the calculation of the burst true energy scales as well as the true event rate. The beaming-corrected energy is given by, \( E_\text{K} = f_\text{det} E_{\text{K,iso}} \), where \( f_\text{det} = 1 - \cos(\theta_j) \) is the beaming correction factor and \( E_{\text{K,iso}} \) is the isotropic-equivalent kinetic energy. At the same time, emission from the relativistic jet is only immediately visible if the observer’s line of sight is inside or intercepts the cone of the outflow. Thus, we expect the true event rate to be larger by a factor of \( f_\text{det}^{-1} \), where \( f_\text{true} = f_\text{det}^{-1} f_\text{obs} \).
In the case of event rates, we correct the observed local rate $\langle N_{\text{obs}} \rangle$ derived from the SGRB luminosity function using the distribution of beaming factors. We note that several works which derive $\langle N_{\text{obs}} \rangle$ via the minimum $\gamma$-ray luminosity (e.g., Guetta & Piran 2006; Nakar et al. 2006; Coward et al. 2012; Wanderman & Piran 2015; Ghirlanda et al. 2019; Liu & Yu 2019), have converged on $\langle N_{\text{obs}} \rangle \approx 0.5 - 10$ Gpc$^{-3}$ yr$^{-1}$. At the lowest end, Ghirlanda et al. (2019) derived $\langle N_{\text{obs}} \rangle \approx 0.5$ Gpc$^{-3}$ yr$^{-1}$ based on available observational constraints of the Fermi SGRB population. However, this lower value is inferred from bright events with $L_{\text{min,iso}} \approx 10^{54}$ erg s$^{-1}$, ignoring a fraction of SGRBs that exhibit fainter luminosities. To account for the contribution of these fainter events with $L_{\text{min,iso}} \approx 10^{49}$ erg s$^{-1}$ (e.g., Guetta & Stella 2009; Wanderman & Piran 2015), we consider a local rate of $\langle N_{\text{obs}} \rangle \approx 10$ Gpc$^{-3}$ yr$^{-1}$ (Nakar et al. 2006) going forward.

Based on events with well-measured opening angles and $\langle N_{\text{obs}} \rangle \approx 10$ Gpc$^{-3}$ yr$^{-1}$, we find a median value of $\langle N_{\text{true}} \rangle = 1786[-1507, +6346]$ Gpc$^{-3}$ yr$^{-1}$ (Figure 5). This derived true event rate is consistent within the errors to previously published values based on SGRBs, albeit is on the high end (Coward et al. 2012; Fong et al. 2014, 2015a; Jin et al. 2018; Dichiara et al. 2020; Figure 5). This can be naturally explained because this rate comprises jet measurements which likely represent the narrower end of the population and ignores the existence of wider jets and lower limits. Thus, $\langle N_{\text{true}} \rangle \approx 1786$ Gpc$^{-3}$ yr$^{-1}$ can actually be considered a high estimate on the true event rate. If instead we use the SGRB mock sample which includes wider jets and is likely a better representation of the parent distribution, we find a lower value of $\langle N_{\text{true, mock}} \rangle = 361[-217, +4367]$ Gpc$^{-3}$ yr$^{-1}$ (Figure 5). Therefore, one would expect the real SGRB event rate to lie between those derived from both the events with jet opening angle measurements and the mock distribution.

6. Discussion

In this section, we discuss the implications of our findings in the context of the event energy scales and potential mechanisms to launch jets. We also compare the SGRB true event rate derived from our study with other observational and theoretical rates published in the literature for these events and BNS/NS–BH mergers. Additionally, we investigate what fraction of the SGRB population can be explained by these mergers.

6.1. Jet Opening Angles: Implications on Energy scales and Potential Launch Mechanism

The jet opening angles uniquely enable a determination of the true, beaming-corrected energy scale of SGRBs, which can be used to probe the energy extraction mechanism to power the jets. The calculation of the true energy for these events is key to discerning between the potential mechanisms to launch relativistic outflows (Shibata & Hotokezaka 2019), either by neutrino pair ($\nu\bar{\nu}$) annihilation (Jaroszynski 1993; Mochkovitch et al. 1993; Rosswog & Ramirez-Ruiz 2002) or as a magnetically driven jet (Blandford & Znajek 1977; Rosswog...
et al. 2003; Rezzolla et al. 2011; Siegel & Metzger 2017) since one expects different released energy ranges. From our analysis, we find median beaming-corrected total energy releases of \( E_{\text{true, tot}} \approx (0.3-1) \times 10^{50} \) erg.

In the \( \nu \bar{\nu} \) annihilation scenario, launched jets have expected opening angles of \( \theta_j \sim 5^\circ-30^\circ \) and maximum beaming-corrected energies of \( \sim 10^{50-60} \) erg (Rosswog & Ramirez-Ruiz 2002; Aloy et al. 2005; Birkl et al. 2007; Dessart et al. 2009; Murguia-Berthier et al. 2017). Liu et al. (2015) and Perego et al. (2017) demonstrate that the deposited energy by the \( \nu \bar{\nu} \) mechanism in comparison to the median inferred energy of \( \sim 10^{50} \) erg for detected SGRBs is not sufficient to power jets in these events. Even under the assumption of smaller opening angles of \( \theta_j < 10^\circ \), it is still not sufficient to explain SGRB jets powered by the energy extracted from the \( \nu \bar{\nu} \) annihilation mechanism (Perego et al. 2017). Based on this, the \( \nu \bar{\nu} \) annihilation mechanism is unlikely to be the dominant energy extraction mechanism to launch SGRBs.

On the other hand, magnetohydrodynamic (MHD) processes (i.e., Blandford-Znajek mechanism; Blandford & Znajek 1977) can easily reach larger energy scales of \( \sim 10^{50-52} \) erg (Rosswog 2005; Lee & Ramirez-Ruiz 2007; Ruiz et al. 2016; Siegel & Metzger 2017). We note that there are different predictions for the jet opening angles depending on the outflow’s magnetization (Rosswog & Ramirez-Ruiz 2002; Duffell et al. 2018; Nathanail et al. 2020) with expected \( \theta_j \gtrsim 10^\circ \) for more magnetized jets (Nathanail et al. 2020). In addition, Christie et al. (2019) demonstrated with 3D MHD simulations that poloidal postmerger magnetic fields generate jets with \( \theta_j \sim 6^\circ-13^\circ \) and up to \( E_{\text{kin}} \sim 10^{52} \) erg, while toroidal postmerger magnetic field geometry produces jets with \( E_{\text{kin}} \sim 10^{51} \) erg and \( \theta_j \sim 3^\circ-5^\circ \). Indeed, this last magnetic field configuration of the postmerger disk is consistent with the jet opening angle and energetics found for GRB 170817A (Margutti & Chornock 2021), as well as the rather low efficiency of this event (\( \eta \sim 10^{-3} \); Salafia & Giacomazzo 2021). Polarmetry studies specifically focused on the radio reverse shocks of long GRBs have been essential to reveal their magnetic field configurations and hence the jet launching mechanism (e.g., Granot & Taylor 2005; Laskar et al. 2019). However, this type of studies are particularly difficult for SGRBs as they are fainter and evolve much faster than long GRBs; so in the meantime, energetics can offer strong clues. Indeed, the agreement between the jet energetics and opening angles derived from the MHD scenarios and those inferred from

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**Figure 6.** Upper panel: the SGRB true event rate distributions \( \langle \mathcal{R}_{\text{true}} \rangle \) derived from the opening angle measurements, \( \langle \mathcal{R}_{\text{true, meas}} \rangle = 1786[-1507, +6346] \ Gpc^{-3} \text{yr}^{-1} \) (orange), and mock, \( \langle \mathcal{R}_{\text{true, mock}} \rangle = 361[-217, +4367] \ Gpc^{-3} \text{yr}^{-1} \) (yellow) samples using the observed rate of \( \mathcal{R}_{\text{obs}} = 10 \ Gpc^{-3} \text{yr}^{-1} \). The median value of each distribution is indicated by a black vertical line. Bottom panel: we present a more realistic range of values of \( \mathcal{R}_{\text{true}} \) that extends between the median values of the true event rate distributions derived from the opening angle measurements (vertical black dashed line) and mock samples (vertical gray dashed line). Other published rates are also shown for comparison. In particular, these rates are derived from the detection of gravitational waves generated by BNS and NS–BH mergers (Abbott et al. 2023) computed over the whole O3 run, SGRBs (Fong et al. 2015a; Jin et al. 2018; Dichiara et al. 2020), Galactic BNSs (O’Shaughnessy & Kim 2010; Pol et al. 2020; Grunthal et al. 2021), and the estimates for the BNS and NS–BH merger rates derived from population synthesis simulations by Sarin et al. (2022). 68% confidence levels are represented.
our observations supports this scenario as the main mechanism to launch SGRB jets.

6.2. Derived Event Rates and Implications for Compact Object Merger Progenitors

One of the most important consequences of determining jet geometries is the inference of the true event rate \( R_{\text{true}} \). In particular, the estimate of \( R_{\text{true}} \) for SGRBs can be compared with the rates of BNS (\( R_{\text{BNS}} \)) or NS–BH (\( R_{\text{NS–BH}} \)) mergers derived from Advanced LIGO/Virgo gravitational-wave detections (Abbott et al. 2017a, 2017b, 2017c, 2020b, 2021b, 2023). This provides us with basic information on the fractions of BNS and NS–BH mergers that may power SGRBs and launch jets. Coupled with ejecta masses inferred from kilonovae (Gompertz et al. 2018; Rossi et al. 2020; Rastinejad et al. 2021), the true event rate can also determine the role of BNS/NS–BH mergers in populating the Universe with r-process elements (e.g., Kasen et al. 2017; Hotokezaka et al. 2018; Rosswog et al. 2018).

To date, several works have derived an observed event rate of \( R_{\text{obs}} \approx 0.5–10 \) Gpc\(^{-3}\) yr\(^{-1}\) (e.g., Guetta & Piran 2006; Nakar et al. 2006; Coward et al. 2012; Wanderman & Piran 2015; Ghirlanda et al. 2019; Liu & Yu 2019) using the minimum \( \gamma \)-ray luminosity of SGRBs. However, the lower end of \( R_{\text{obs}} \approx 0.5 \) Gpc\(^{-3}\) yr\(^{-1}\) is derived from the most luminous events. Therefore, for calculating the SGRB true event rate from the jet opening angle measurements and mock distributions, we choose the value of \( R_{\text{obs}} \approx 10 \) Gpc\(^{-3}\) yr\(^{-1}\) (assuming \( L_{\text{iso, min}} \approx 10^{49}\) erg s\(^{-1}\); Nakar et al. 2006), which has been used in previous literature (Metzger & Berger 2012; Fong et al. 2015a; Mandel & Broekgaarden 2022). In Figure 6, we present our distributions of \( R_{\text{true}} \) and compare these rates with BNS and NS–BH merger rates published in the literature as well as previous SGRB studies. We use the range of rates, \( R_{\text{true}} \approx 361–1786 \) Gpc\(^{-3}\) yr\(^{-1}\), where the lower end is set by the mock sample including wider jets, while the upper end is set by jet measurements only. This range is fully consistent with the estimated range of Galactic BNS merger rates (O’Shaughnessy & Kim 2010; Pol et al. 2020; Grunthal et al. 2021) and the BNS merger rate derived from the detection of gravitational waves (Figure 6; Abbott et al. 2023). This implies that SGRBs are predominantly the result of BNS mergers with successfully launched relativistic jets, with the most successful direct evidence being the joint detection of the BNS merger GW170817 with its SGRB (GRB 170817A; Abbott et al. 2017a).

An open question remains on the fraction of SGRBs which are derived from NS–BH mergers. Thus far, the identification of electromagnetic (EM) counterparts to the few known GW-detected NS–BH mergers, GW200105 and GW200115 (e.g.,
Anand et al. 2021; Dichiara et al. 2021; Rastinejad et al. 2021) have not been made. Theoretically, one expects the partial or complete disruption of the NS by the BH, resulting in little or no ejected matter and EM emission (e.g., Foucart 2012). However, there are conditions for which NS–BH mergers can produce successful SGRBs and/or EM emission in simulations (e.g., Bhattacharya et al. 2019; Barbieri et al. 2020; Darbha et al. 2021). Observational studies have also hinted at the possibility of an NS–BH merger contribution from the population of SGRBs with EE (Gompertz et al. 2020). However, from Figure 6, our SGRB range of rates are between 2 and 13 times larger than the upper ends of the NS–BH merger rate distributions inferred from both GW observations (Abbott et al. 2023) and population synthesis simulations (Sarin et al. 2022). Therefore, our results only support that (at most) a small fraction of SGRBs originate from NS–BH mergers (Figure 6).

In our study, we also uncovered a group of SGRBs with inferred jet opening angles of \( \theta_j \gtrsim 10^\circ \), which are broader than the derived median of jet opening angle measurements of \( \langle \theta_j \rangle \approx 6^\circ \). For most of these cases, the lower limits on the opening angles were inferred thanks to late-time X-ray detections obtained at \( t_j > 10 \) days. As seen in our study, the inclusion of even a few wide jets pushes the inferred true event rates to lower values, which has consequences for the progenitors of SGRBs. Additionally, successful jets from NS–BH mergers are expected to be wider (\( \theta_j \approx 25^\circ–30^\circ \)), due to the lower densities of the surrounding environment (Murguia-Berthier et al. 2017). In addition, the widest jets are expected to originate from mergers containing highly spinning BHs (Murguia-Berthier et al. 2017; Ruiz et al. 2018). However, jets wider than \( \approx 30^\circ \) are not expected to survive routinely, resulting in a failed or choked jet (Ghirlanda et al. 2019). Thus, continued X-ray monitoring of cosmological SGRBs to late times, in tandem with monitoring of future GW-detected SGRBs events, will be imperative in constraining the true population of wide jets.

### 7. Conclusions

We have presented a comprehensive compilation of Swift SGRBs discovered between 2005 and 2021, and observed with Chandra and XMM-Newton at late times (\( \delta t > 0.8 \) days). We conclude our findings below.

1. From the 29 SGRBs in our final sample, 18 were observed by Chandra, four by XMM-Newton, and seven by both observatories, resulting in 60 epochs that we uniformly analyzed, across all events at \( \delta t > 0.8 \) days.
2. Using broadband information and applying the synchrotron afterglow model, we find \( n_0 \approx 0.7 \times 10^{-5} \)–\( 0.7 \times 10^{-4} \) cm\(^{-3} \) and \( E_{K,iso} \approx 3 \times 10^{49}–1.7 \times 10^{50} \) erg, and median values of \( n_0 \approx 6.4 \times 10^{-4} \) cm\(^{-3} \) and \( \langle E_{K,iso} \rangle \approx 4.0 \times 10^{50} \) erg.
3. We identify nine SGRBs (050724A, 051221A, 111020A, 130603B, 140903A, 150424A, 160821B, 200411A, and 200522A) with significant steepenings in their X-ray light curves that are best explained by jet breaks, two of which are new identifications (SGRBs 050724A and 200411A). Including the wide-angle GRB 211106A with an identified break in its radio afterglow light curve, we find a range of jet-break times between \( \approx 0.1 \) and 30 days after the bursts, translating to \( \langle \theta_j, det \rangle = 6^\circ.1[-3^\circ.2, +9^\circ.3] \) (68% confidence on the entire distribution).

4. From the nondetection of jet breaks for 19 events, we derive lower limits on the opening angles of \( \theta_j \gtrsim 0^\circ.3–26^\circ \), including 12 new limits. Of particular interest are six events with wide inferred opening angles of \( \theta_j \gtrsim 10^\circ \). Coupled with two wide-angle events, SGRBs 050724A and 211106A with \( \theta_j \approx 34^\circ \) and \( 16^\circ \), respectively, we have unveiled a growing population of SGRBs with wide jets.

5. We obtain beaming-corrected total true energies between \( E_{truen,tot} \approx 10^{49}–10^{50} \), which are consistent with MHD processes as the mechanism of energy extraction to launch jets.
6. We derive a range for beaming-corrected true event rates of \( \mathcal{R}_{true} \approx 361 - 1786 \) Gpc\(^{-3} \) yr\(^{-1} \), for which the low end is set by the inclusion of wider jets, and the upper end is set by including jet measurements alone. These rates are fully consistent with the rates of BNS mergers derived from GW events, as well as the rates of Galactic BNS mergers. This aligns with expectations that the predominant progenitor channel of SGRBs is BNS mergers. It is also plausible, although cannot be confirmed given the current rate uncertainties, that most BNS mergers produce successful SGRB jets.

7. The SGRB event rate is between 2 and 13 times larger than the GW-derived NS–BH merger rate. Thus, we find that (at most) a small fraction of SGRBs could originate from these mergers.

Our study highlights the importance of the late-time X-ray monitoring of SGRBs in constraining the beaming angles of SGRBs. SGRBs not only exhibit narrow opening angles of \( \approx 6^\circ \), but are also capable of launching broader jets with opening angles of \( \gtrsim 10^\circ \). In recent years, a concerted effort has been made to follow up SGRB X-ray afterglows beyond 1 day after the burst trigger, when they are expected to be fainter and exhibit breaks. This has resulted in a substantial increase in the number of jet opening angle measurements and meaningful lower limits. Additionally, the exceptional coordination between the most sensitive space- and ground-based telescopes has allowed us to perform broadband monitoring of these events, providing constraints on the burst energetics and environmental properties. Relative to Swift/XRT, the exceptional sensitivity of Chandra and XMM-Newton has enabled monitoring up to 60 days after the burst in some cases. Moreover, the high spatial resolution of Chandra enables us to disentangle the afterglow from any contaminating X-ray source. The combined capabilities of these observatories has enabled studies to confront different jet launching mechanisms and further understand their NS merger progenitors. The next generation of X-ray missions like NewAthena and XRISM will be indispensable to maintain sensitivity to late jet breaks, and thus wider jets.

Our study provides a baseline for the geometries of successfully launched jets from mergers. The first and only joint detection of GW170817/SGRB 170817A with a successfully launched jet (Abbott et al. 2017a; Goldstein et al. 2017; Savchenko et al. 2017) enabled a tight constraint on the opening angle of \( \approx 2^\circ–4^\circ \), and evidence for jet structure (e.g., Lamb & Kobayashi 2017; Alexander et al. 2018; D’Avanzo et al. 2018; Margutti et al. 2018; Troja et al. 2018; Xie et al. 2018; Fong et al. 2019; Ghirlanda et al. 2019; Hajela et al. 2019). In tandem with the past two decades of SGRB observations, the upcoming observing run (O4) of Advanced
LIGO/Virgo/KAGRA (Abbott et al. 2020a) and beyond will undoubtedly provide a complementary view on the progenitor conditions necessary to launch jets.

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Software: CIAO software package (v.4.12; Fruscione et al. 2006), emcee package (Foreman-Mackey et al. 2013, 2019), HEASoft software (v.6.17; Blackburn et al. 1999; NASA High Energy Astrophysics Science Archive Research Center (Heasarc), 2014), NumPy (van der Walt et al. 2011), Pandas (McKinney 2010), Matplotlib (Hunter 2007), SAS software (v.18.0.0; Gabriel et al. 2004), and XSPEC (Arnaud 1996).

Appendix A

Fitting Models for the X-Ray Afterglow Light Curves

The following lines show the models used to fit the X-ray afterglow light curves in Section 4.1.

1. Single power-law model:
   
   \[ F_X = C t^{\alpha_1} \]  

2. Broken power-law model:
   
   \[ F_X = C \left( \frac{t}{t_{b1}} \right)^{-\alpha_1} + \left( \frac{t}{t_{b1}} \right)^{-\alpha_2} \left( \frac{t}{t_{b2}} \right)^{-1/s_1} \]

3. Triple power-law model:
   
   \[ F_X = C \left( \frac{t}{t_{b1}} \right)^{-\alpha_1} + \left( \frac{t}{t_{b1}} \right)^{-\alpha_2} \left( \frac{t}{t_{b2}} \right)^{-\alpha_3} \left( \frac{t}{t_{b3}} \right)^{-1/s_2} \]

where $F_X$ is the X-ray unabsorbed flux (erg s$^{-1}$ cm$^{-2}$) of the afterglow, $C$ is the normalization or amplitude, $\alpha_i$ ($i = 1, 2, 3$) correspond to the temporal decay index, $t_{bj}$ ($j = 1, 2$) are the break times (in seconds), and $s_j$ are the constant smoothness parameters ($s = -10$ or $s = 10$, depending if the change in slope between power-law segments is positive or negative, respectively). We note that the break times are not necessarily classified as jet breaks at this point in the process.

Appendix B

F-test Chart Flow

In Section 4.1, we apply an F-test to discern which is the best-fit model between the three different fitting models used in this work (see Appendix A). Thus, we establish an F-test null hypothesis ($H_0$) in which we accept that a simpler model is better to describe the data. Treatment the $\chi^2$ values from each fit as random variables that follow an F-distribution, we can define an F-statistic value assuming the ratio between them:

\[ F_{\text{stat}} = \frac{(\chi^2_1 - \chi^2_2)/(n_2 - k_2)}{(\chi^2_2)/(n_1 - k_1 - k_2)}. \]

where $\chi^2_1$ is the $\chi^2$ value of the simpler model, $\chi^2_2$ corresponds to the $\chi^2$ value of the more complex model, $k_1$ and $k_2$ are the numbers of variables in the simpler and more complex models, respectively, and $n$ is the number of data points. We also compute a critical value ($F_{\text{crit}}$) with a confidence interval of 95% ($\alpha = 0.05$) and compare it against $F_{\text{stat}}$ to accept or reject $H_0$. If $F_{\text{stat}} > F_{\text{crit}}$, we then reject $H_0$ and accept the alternate hypothesis ($H_1$), i.e., we need a more complex model to describe the GRB light curve. Since we have three different models (simple, broken and triple power-law models), we follow the flow chart in Figure 7 to determine which of those models best describes the SGRB light curve.

Appendix C

X-Ray Observations of GRB 130603B

In the case of GRB 130603B, a late-time Chandra observation at 6.7 years post-trigger unveiled the presence of an X-ray contaminant to the afterglow light curve (Figure 8).
Figure 8. X-ray imaging panel of GRB 130603B. The XMM-Newton/PN observations (left and middle) at \( t \sim 2.7 \) and \( t \sim 7.0 \) days in the 0.3–10 keV energy band, and merged Chandra/ACIS-S observation (right) obtained at \( t \sim 6.7 \) yr in the 0.5–7 keV energy band. The blue circle indicates the XMM-Newton source region. The small dashed red region in the images shows the contaminating source (X1), which is resolved in the Chandra observation. The final X-ray flux afterglow light curve is corrected against the extra contribution of this contaminant with unabsorbed X-ray flux of \((9.2^{+1.2}_{-1.1}) \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}\), which was not taken into account in earlier works.

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