GAMMA-RAY BURST ENERGETICS IN THE SWIFT ERA

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ABSTRACT

We examine the rest-frame energetics of 76 gamma-ray bursts (GRBs) with known redshift that were detected by the Swift spacecraft and monitored by the satellite’s X-Ray Telescope (XRT). Using the bolometric fluence values estimated by Butler and coworkers and the last XRT observation for each event, we set a lower limit to their collimation-corrected energy $E_c$, and find that 68% of our sample is at high enough redshift and/or low enough fluence to accommodate a jet break occurring beyond the last XRT observation and still be consistent with the pre-Swift $E_c$, distribution for long GRBs. We find that relatively few of the X-ray light curves for the remaining events show evidence for late-time decay slopes that are consistent with that expected from post-jet break emission. The breaks in the X-ray light curves that do exist tend to be shallower and occur earlier than the breaks previously observed in optical light curves, yielding a $E_c$ distribution that is far lower than the pre-Swift distribution. If these early X-ray breaks are not due to jet effects, then a small but significant fraction of our sample have lower limits to their collimation-corrected energy that place them well above the pre-Swift $E_c$ distribution. Either scenario would necessitate a much wider post-Swift $E_c$ distribution for long cosmological GRBs compared to the narrow standard energy deduced from pre-Swift observations. We note that almost all of the pre-Swift $E_c$, estimates come from jet breaks detected in the optical whereas our sample is limited entirely to X-ray wavelengths, furthering the suggestion that the assumed achromaticity of jet breaks may not extend to high energies.

Subject headings: gamma rays: bursts

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1. INTRODUCTION

As of 2007 June, the Swift spacecraft’s Burst Alert Telescope (BAT; Gehrels et al. 2004; Barthelmy et al. 2005b) had detected over 200 gamma-ray bursts (GRBs) and followed >80% with the satellite’s X-Ray Telescope (XRT; Burrows et al. 2005a). The data that have accumulated as a result of the huge success of the XRT have shown that the X-ray light curves of GRB afterglows are far more complex than previous observations (e.g., Frontera et al. 2000; Gendre et al. 2006) had indicated. Large drops in the X-ray emission immediately following a GRB (Barthelmy et al. 2005a) are superseded by a shallow decay (Granot et al. 2006), ultimately giving way to the late-time afterglow light curve observed by pre-Swift X-ray instruments. In many cases these light-curve phases are punctuated by flaring activity occurring hundreds to thousands of seconds after the initial energy release (Burrows et al. 2005b). Yet in other cases only a single light-curve phase manifests, yielding an uninterrupted power-law decline that extends directly from the prompt gamma-ray emission into the X-ray regime lasting several days to weeks after the event (Schady et al. 2007; Sato et al. 2007; Mundell et al. 2007; Holland et al. 2007).

Relatively few of these XRT-monitored afterglow light curves have shown properties consistent with the late-time steepening that had been observed to occur in the optical light curves of pre-Swift GRBs (Harrison et al. 1999; Stanek et al. 1999). This sharp drop in the flux of some pre-Swift afterglows has been interpreted as a sign of the deceleration and/or lateral expansion of a highly collimated relativistic outflow (Rhoads 1997). The existence of such a jet structure in the GRB outflow has become an integral part of the theoretical description of these events (Mészáros 2002), and indeed a necessary component to explain the enormous amount of radiated energy inferred if the prompt emission is assumed to be isotropic (Waxman et al. 1998; Fruchter et al. 1999).

Several authors have examined the presence, or lack thereof, of jet breaks in the X-ray afterglow light curves collected by the XRT. Burrows et al. (2007) examined the X-ray light curves of ~150 GRB afterglows and concluded that the “canonical” jet model behavior, consisting of an achromatic light-curve break between $t_{\text{jet}} \sim 1$ and 4 days and a postbreak power-law decay index $F_\nu \propto t^{-\alpha}$ steeper than $\alpha = 2.0$ (Rhoads 1997; Sari et al. 1999), is extremely rare. They find that many of these X-ray light curves do exhibit breaks, but that they occur at about $10^4$ s, far earlier than the jet breaks observed at optical wavelengths of pre-Swift GRBs. These early breaks are typically followed by power-law decays which are shallower than the minimum decay index predicted by simple jet models. In all, the preliminary analysis done by Burrows et al. (2007) revealed only six events with light-curve breaks that were consistent with theoretical predictions of jet break behavior. Subsequently, Panaitescu (2007) performed a similar analysis of 236 GRB afterglows and found 30 events which were consistent with the behavior expected from standard jet models. He also reported an additional 27 events with potential jet breaks, for which the spectral and temporal properties were not entirely consistent with model predictions, and another 38 events which exhibited no temporal breaks in their X-ray light curves. In all, Panaitescu concludes that some 60% of well-monitored X-ray afterglows exhibit some evidence for a potential late-time jet break.

Recently, Butler et al. (2007) reported on the first comprehensive catalog of bolometric energy fluences of GRBs detected by the BAT instrument. One implication of that analysis is that a significant fraction of the Swift events with known redshift $z$ are underenergetic relative to pre-Swift events. This is likely due to a factor of 3–10 greater sensitivity and the lower resulting detection threshold of the BAT relative to previous instruments. (e.g., Barthelmy et al. 2005b). One consequence of this higher
sensitivity may be a capacity to detect a greater fraction of more distant, high-z events. Both of these effects, a lower $E_{\text{iso}}$ and a higher $z$, have the effect of increasing the predicted jet break time $t_{\text{jet}}$ given a fixed collimation angle, or, more importantly, a standard collimation-corrected energy $E_{\gamma}$.

In this paper we examine the source frame energetics of 76 GRBs detected by the Swift spacecraft with known redshift. Using the bolometric fluence values estimated in Butler et al. (2007) and the last XRT observation, we calculate a lower limit $E_{\gamma}$ for our entire sample to determine the fraction of Swift events that could accommodate a jet break beyond the last XRT observation and still be consistent with the relatively narrow pre-Swift $E_{\gamma}$ distribution found by Frail et al. (2001) and Bloom et al. (2003). To analyze the breaks that do exit in a subset of light curves, we employ a Bayesian blocks algorithm (Scargle 1998; Butler & Kocevski 2007) to fit the various segments of XRT light curves, allowing for an automated and robust approach to measuring break times, as well as and prebreak and postbreak power-law indices in the afterglow decay. We find that the higher sensitivity of the BAT instrument allows for a large fraction, roughly $\sim 68\%$, of our sample to accommodate a jet break beyond the last XRT observation and still have an energy consistent with the relatively narrow pre-Swift $E_{\gamma}$, distribution found by Frail et al. (2001) and Bloom et al. (2003).

Using the bolometric fluence values estimated in Butler et al. (2007), we apply our analysis. The reduction from cleaned event lists output by the xrtpipeline code and from the HEAsoft BAT software to the $E_{\gamma}$ distribution which has a median value that is lower than that of the pre-Swift sample. We find that the energetics predicted by most of the breaks reported by Panaitescu (2007) suffer from the same difficulties. The assumed validity of the narrowness of the pre-Swift $E_{\gamma}$ distribution casts doubt on the interpretation of many of these early temporal breaks as jet breaks, unless the intrinsic spread in the collimation-corrected energy is much wider than had previously been reported. We discuss our data acquisition and reduction techniques in § 2 and expand on our results in § 3. We discuss the implications of these results in § 4.

2. DATA AND ANALYSIS

We form a sample of 76 GRBs detected by Swift with redshifts reported to the Gamma-Ray Bursts Coordinates Network (GCN) circulars. The entire list of bursts, including redshifts and their associated references, can be found in Table 1. For these, and all other Swift events, we download the BAT and XRT data products from the Swift Archive and process the data with version 0.10.3 of the xrtpipeline reduction script and other tools from the HEAsoft version 6.0.3 software release. We employ the calibration files from the 2006 October 14 BAT database release for this analysis. The reduction from cleaned event lists output by the xrtpipeline code and from the HEAsoft BAT software to science-ready light curves and spectra is described in extensive detail in Butler & Kocevski (2007). All of our resulting BAT spectral fits and X-ray light curves to which we apply our analysis are publicly available.4 The error regions reported throughout the paper correspond to the 90% confidence interval.

2.1. BAT Spectral Fitting

A full and extensive description of the fitting methods used to estimate the bolometric fluence $S_{\text{bol}}$ values for our sample of

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2 See ftp://legacy.gsfc.nasa.gov/swift/data.
3 See http://heasarc.gsfc.nasa.gov/docs/software/heasoft/.
4 See http://astro.berkeley.edu/~nat/swift.

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| GRB | Redshift | log $E_{\text{iso}}$ (ergs) | log $t_{\text{jet}}$ (s) | log $E_{\gamma}$ (ergs) |
|-----|----------|-----------------------------|--------------------------|-------------------------|
| 050126 | 1.29 | 51.88 (0.13, 0.38) | 4.77 | >51.90 |
| 050315 | 1.95 | 52.75 (0.00, 0.33) | 5.98 | >53.05 |
| 051111 | 1.55 | 52.76 (0.12, 0.28) | 4.67 | >52.33 |
| 051111 | 0.55 | 51.45 (0.19, 0.24) | 5.86 | >51.33 |
| 051221A | 0.71 | 51.07 (0.26, 0.36) | 5.21 | >51.34 |
| 060116A | 3.53 | 52.73 (0.03, 0.19) | 5.40 | >52.39 |
| 060502A | 4.05 | 52.61 (0.07, 0.11) | 6.57 | >52.89 |
| 060502B | 3.91 | 52.51 (0.14, 0.27) | 6.20 | >52.81 |
| 060522A | 1.95 | 52.75 (0.00, 0.33) | 4.75 | >52.46 |
| 060522B | 1.49 | 53.01 (0.10, 0.23) | 5.52 | >53.17 |
| 060502A | 3.53 | 52.73 (0.03, 0.19) | 5.40 | >52.39 |
| 060604A | 2.68 | 51.70 (0.09, 0.53) | 5.90 | >50.66 |
| 060605A | 3.78 | 52.39 (0.13, 0.35) | 4.84 | >51.85 |
| 060607A | 3.08 | 52.95 (0.08, 0.25) | 5.30 | >52.68 |
| 060614A | 0.12 | 51.39 (0.09, 0.06) | 5.85 | >51.17 |
| 060707A | 3.43 | 52.77 (0.06, 0.13) | 6.23 | >52.95 |
| 060708A | 1.80 | 51.81 (0.19, 0.19) | 5.80 | >51.18 |
| 060714A | 2.71 | 52.88 (0.05, 0.30) | 5.81 | >51.82 |
| 060720A | 0.54 | 51.52 (0.08, 0.28) | 7.12 | >51.60 |
| 060902A | 0.70 | 51.49 (0.11, 0.20) | 5.27 | >51.76 |
| 060906A | 3.68 | 53.10 (0.04, 0.30) | 4.85 | >53.17 |
| 060908A | 2.43 | 52.84 (0.09, 0.19) | 5.90 | >52.53 |
| 060912A | 0.94 | 51.90 (0.14, 0.21) | 5.39 | >51.95 |
| 060926A | 3.21 | 51.97 (0.09, 0.55) | 5.06 | >51.99 |
| 060927A | 5.47 | 52.93 (0.07, 0.09) | 3.79 | >52.98 |
| 061005A | 3.30 | 52.30 (0.06, 0.20) | 5.17 | >52.26 |
| 061007A | 1.26 | 54.18 (0.24, 0.22) | 5.78 | >54.47 |
| 061028A | 0.76 | 51.36 (0.12, 0.36) | 4.39 | >51.01 |
| 061100B | 3.44 | 53.15 (0.36, 0.31) | 4.21 | >53.42 |
| 061121A | 1.31 | 53.27 (0.11, 0.21) | 6.34 | >53.31 |
TABLE 1—Continued

| GRBa   | Redshiftb | log $E_{\text{iso}}$ (ergs) | log $t_{\text{XRT}}$ (s) | log $E_{\gamma, \text{XRT}}$ (ergs) |
|--------|-----------|-------------------------------|--------------------------|---------------------------------|
| 061126........ | 1.16*     | 52.87 (0.15, 0.29)           | 6.13                     | >52.38                          |
| 061210j........ | 0.41*     | 51.05 (0.43, 0.35)           | 5.58                     | >50.54                          |
| 061217j........ | 0.83*     | 50.50 (0.42, 0.34)           | 4.12                     | >50.18                          |
| 061222B........ | 3.36      | 53.00 (0.18, 0.19)           | 4.77                     | >53.08                          |
| 070110........ | 2.25      | 52.47 (0.09, 0.27)           | 6.36                     | >52.69                          |
| 070208........ | 1.17      | 51.45 (0.14, 0.26)           | 5.30                     | >51.09                          |
| 070306........ | 1.50*     | 52.78 (0.08, 0.28)           | 6.06                     | >50.55                          |
| 070318........ | 0.84      | 51.96 (0.12, 0.29)           | 6.00                     | >52.25                          |
| 070411j........ | 2.95      | 53.01 (0.09, 0.25)           | 5.84                     | >53.31                          |
| 070419A........ | 0.97      | 51.38 (0.11, 0.28)           | 3.07                     | >51.44                          |
| 070506........ | 2.31      | 51.41 (0.10, 0.22)           | 3.91                     | >51.47                          |
| 070508........ | 0.82*     | 52.89 (0.07, 0.08)           | 5.51                     | >53.18                          |

a Short GRBs are denoted by a dagger and are excluded from our primary analysis.
b Photometrically determined redshifts are marked with a double dagger. Redshifts determined through host association are denoted with an asterisk.
c The last 3 σ detection of the afterglow by the XRT.
d The lower limit on $E_{\gamma}$ when using the last XRT observation as the lower limit to the jet break time.

2.2. X-Ray Light-Curve Region Selection and Fitting

In order to measure the temporal power-law indices $L \propto t^{-\alpha}$ of separate segments in the X-ray light curve, we fit the X-ray light-curve data using an extension of the Bayesian blocks algorithm (Scargle 1998) to piecewise logharmonic data. Developed in Butler & Kocevski (2007), the algorithm determines the most likely multisegment power-law fit consistent with the light curves, without the need for human intervention. The final result of the fitting routine for a sample of events can be seen in Figure 1, where individual light-curve segments have been automatically determined and fit to power laws of various indices. For each break, we record the time of occurrence along with the prebreak and postbreak power-law indices, $\alpha_1$ and $\alpha_2$. The time of the last 3 σ detection $t_{\text{XRT}}$ of the source by the XRT is also recorded for each event, although this determination does not depend on the Bayesian block algorithm. The prebreak and postbreak $\alpha$, the time of the break, and $t_{\text{XRT}}$ are listed in Tables 1 and 2, where available.

2.3. Isotropic and Collimation-Corrected Energy Calculations

We calculate the total isotropic equivalent energy $E_{\text{iso}}$ emitted by the GRB from the measured fluence $S_{\text{bol}}$ through the standard equation

$$E_{\text{iso}} = 4\pi D_l^2 \left(\frac{1}{1+z}\right) S_{\text{bol}} k,$$

where $D_l$ is the luminosity distance at redshift $z$ and $k$ represents the multiplicative factor or order unity that translates the bandpass of the detector in the observer frame to a standard rest-frame bandpass, here chosen to be $1-10^4$ keV (Bloom et al. 2001). We employ the method outlined in Amati et al. (2002) to calculate $k$.

For the case of a homogeneous circumburst medium (Sari et al. 1999) the observed jet break time $t_{\text{jet}}$ is related to the jet opening angle $\theta_{\text{jet}}$ through

$$t_{\text{jet}} = 0.101 \left(\frac{t_{\text{jet}}}{1 \text{ day}}\right)^{3/8} \left(\frac{\xi}{0.2}\right)^{1/8} \left(\frac{n}{10 \text{ cm}^{-3}}\right)^{1/8} \left(\frac{1+z}{2}\right)^{-3/8} \left(\frac{E_{\text{iso}}}{10^{51} \text{ ergs}}\right)^{-1/8},$$

where $\xi$ represents the efficiency of converting the blast wave’s kinetic energy into gamma rays and $n$ is the circumburst density.

Throughout our analysis, we have chosen to assume a fixed value for both the efficiency and density parameters, using $\xi = 0.5$ and $n = 3.0$ (Granot et al. 2006; Kumar et al. 2007). However, varying these assumptions within reasonable ranges ($\xi = 0.1-1.0$ and $n = 3.0-30$) has little effect on our final results. The conversion from $E_{\text{iso}}$ to the collimation-corrected energy $E_{\gamma}$ is then a simple geometric correction given by

$$E_{\gamma} = E_{\text{iso}} (1 - \cos \theta_{\text{jet}}).$$

We assume a cosmology with $h = 0.71$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$ throughout.

3. RESULTS

The redshift distribution of all 76 GRBs detected by Swift in comparison to the 48 pre-Swift GRBs (Friedman & Bloom 2005)

5 Similar light curves are available for all Swift bursts at http://astro.berkeley.edu/~nat/swift.
is shown in Figure 2. The median redshift of the Swift-detected events is \( z = 1.8 \) with a standard deviation \( \sigma = 1.59 \) compared to the median pre-Swift redshift of \( z = 1.1 \) and \( \sigma = 0.98 \). A Kolmogorov-Smirnov (K-S) analysis gives the associated probability that the two distributions are consistent to be exceedingly small, at \( p = 0.015 \).

For the purposes of comparing our \( E_{\text{iso}} \), and eventually \( E_{\gamma} \), estimates to those of pre-Swift GRBs with known redshift, which consist almost exclusively of long-duration events, we form a subset of long bursts (LBs) from our original sample of 76 Swift GRBs. For this set we exclude nine events which have been classified as short bursts (\( t_{90} < 2 \) s), another three events which are peculiarly underluminous (XRF 060218, GRB 050826, and GRB 051109B), and one event (GRB 060124) for insufficient BAT coverage during the prompt emission (see Butler et al. 2007 for more details), leaving a total of 63 LB events. A plot of \( E_{\text{iso}} \) versus redshift for all detected pre-Swift and post-Swift events (long, short, and SN-associated GRBs) is shown in Figure 3.

The distribution of \( E_{\text{iso}} \) for the Swift-detected GRBs marginally extends to lower energies compared to the pre-Swift sample, even after the admittedly ad hoc exclusion of peculiarly underluminous events. The median \( E_{\text{iso}} \) value of the Swift sample is roughly \( 4.11^{+2.53}_{-2.52} \times 10^{52} \) ergs compared to \( 7.76^{+9.01}_{-1.20} \times 10^{52} \) ergs for the pre-Swift sample. A K-S test returns a probability of \( p = 0.093 \). The inclusion of the underluminous LB events only worsens the disparity between the two samples.

How does the observed increase in the median redshift and the decrease in the median \( E_{\text{iso}} \) of the Swift-selected sample effect where we should expect to observe jet breaks in the XRT data? From equations (2) and (3) we can see that

\[
\frac{t_{\text{jet}}}{\cos^{-1} \left( 1 - \frac{E_{\gamma}}{E_{\text{iso}}} \right)} \approx 452 \left( \frac{E_{\text{iso}}}{10^{53} \text{ ergs}} \right)^{-1/8} \times \frac{1 + z}{2} \left( \frac{E_{\text{iso}}}{10^{53} \text{ ergs}} \right)^{-1/3} \left( \frac{n}{10} \right)^{-1/3}. 
\]

Given a fixed \( E_{\gamma} \), both effects should increase the observed delay between the initial explosion and the subsequent steepening of the afterglow light curve. There is sufficient evidence from pre-Swift observations to suggest that \( E_{\gamma} \) has a narrow range of values for typical long GRBs. Using the measured \( t_{\text{jet}}, E_{\text{iso}}, \) and \( z \) for a sample of 17 bursts, Frail et al. (2001) and later Bloom et al. (2003) concluded that this geometrically corrected energy is narrowly clustered around a standard energy, which Bloom et al. (2003) report as \( E_{\gamma} = 1.33 \times 10^{51} \) ergs with a variance of 0.35 dex. Assuming this pre-Swift-determined value, and its variance, we...
greater sensitivity of the BAT instrument.

can calculate the expected $t_{\text{jet}}$ distribution for our Swift-detected sample.

A histogram of the ratio between this expected $t_{\text{jet}}$ and the last $3 \sigma$ XRT observation $t_{\text{XRT}}$ is shown Figure 4. Most events, when assuming a fixed $E_\gamma$, have an expected $t_{\text{jet}}$ that is near or beyond the last significant XRT detection. The median expected $t_{\text{jet}}$ is 10.37 days after the GRB, leading 63% of our LB sample to have an expected $t_{\text{jet}}$ that occurs beyond the last $3 \sigma$ XRT detection. Three events in our LB subset were excluded from this analysis because their $E_{\text{iso}}$ values were below $1.33 \times 10^{51}$ ergs and therefore could not accommodate an $E_\gamma$ that was consistent with the pre-Swift energetics distribution. Such a high ratio of events with $t_{\text{jet}} > t_{\text{XRT}}$ is somewhat surprising, given that the median duration of XRT observations is typically an order of magnitude longer than the pre-Swift $t_{\text{jet}}$ distribution. A comparison of $t_{\text{XRT}}$ for our LB sample to the pre-Swift $t_{\text{jet}}$ is shown in Figure 5, with the pre-Swift jet breaks shown as the filled histogram. The medians of the two distributions differ by roughly an order of magnitude.

What of the light-curve breaks that do exist in our LB sample? Of the 20 GRBs, or $\sim 37\%$ of our sample, for which the expected $t_{\text{jet}} < t_{\text{XRT}}$, only three were determined by Panaitescu (2007) to have jet breaks that are consistent with the standard jet model, five events were classified as containing potential jet breaks, and four events showed no evidence for late-time breaks in their light

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**TABLE 2**

| GRB   | Redshift | log $t_{\text{jet}}$ (s) | $\alpha_1$ | $\alpha_2$ | log $E_\gamma$ (ergs) |
|-------|----------|--------------------------|------------|------------|----------------------|
| First Group |
| 050315 | 1.95     | 5.41                     | 0.64       | 1.91       | 50.72                |
| 050318 | 1.44     | 4.41                     | 1.35       | 2.06       | 49.56                |
| 050319 | 3.24     | 4.78                     | 0.67       | 1.71       | 50.05                |
| 050505 | 4.27     | 4.84                     | 1.27       | 1.90       | 50.43                |
| 050730 | 3.97     | 4.11                     | 0.82       | 2.57       | 49.73                |
| 050803 | 0.42     | 4.11                     | 0.29       | 1.76       | 48.96                |
| 050814 | 5.30     | 4.94                     | 0.81       | 2.24       | 50.11                |
| 051022 | 0.80     | 5.41                     | 1.40       | 2.18       | 51.54                |
| 060526 | 3.21     | 5.11                     | 0.89       | 2.91       | 50.34                |
| 060605 | 3.78     | 4.11                     | 1.04       | 2.10       | 49.33                |
| 060614 | 0.12     | 5.11                     | 1.29       | 2.14       | 49.79                |
| 060906 | 3.68     | 4.24                     | 0.43       | 1.81       | 49.96                |
| 070308 | 1.50     | 4.78                     | 1.20       | 1.91       | 50.33                |
| Second Group |
| 050401 | 2.90     | 3.39                     | 0.66       | 1.38       | 49.69                |
| 050408 | 1.24     | 4.55                     | 0.70       | 1.00       | 49.50                |
| 050525A| 0.61     | 3.78                     | 0.91       | 1.39       | 49.37                |
| 050603 | 2.82     | 4.83                     | 1.40       | 1.70       | 50.90                |
| 050802 | 1.71     | 3.81                     | 0.73       | 1.25       | 49.18                |
| 051016B| 0.94     | 4.80                     | 0.80       | 1.17       | 48.74                |
| 060210 | 3.91     | 4.67                     | 0.98       | 1.28       | 50.65                |
| 060218 | 0.03     | 4.73                     | 0.82       | 1.23       | 47.32                |
| 060707 | 3.43     | 4.72                     | 0.60       | 1.05       | 50.09                |
| 060708 | 1.80     | 4.20                     | 0.74       | 1.38       | 49.13                |
| 070125 | 1.55     | 5.11                     | 0.90       | 1.60       | 51.49                |
| 070318 | 0.84     | 5.44                     | 1.17       | 1.71       | 50.31                |

* The first group consists of GRBs with spectral and temporal behavior found by Panaitescu (2007) to be consistent with standard jet models. The second group has light-curve breaks that are not fully consistent with model predictions but exhibit steepening that resembles jet break behavior.
curve. The remaining events in this subset have insufficient coverage to test for the existence of jet breaks. Of these eight events that do show some steepening in their light curves, all have breaks that occur earlier than the expected $t_{\text{jet}}$, indicating that their $E_\gamma$ values must be lower than the assumed standard energy determined from pre-Swift GRBs. Of the 43 GRBs, or $\sim 63\%$ of our sample, for which the expected $t_{\text{jet}} > t_{\text{XRT}}$, eight were determined by Panaitescu (2007) to have jet breaks that are consistent with the standard jet model, with three events containing potential jet breaks. For these 11 events with some sign of steepening, their interpretation as jet breaks will necessarily yield $E_\gamma$ values that are far less than the narrow peak of the pre-Swift $E_\gamma$ distribution because their expected $t_{\text{jet}}$ is greater than the last XRT observation.

We examine the $E_\gamma$ distribution resulting from the use of these early light-curve breaks as potential jet breaks, regardless of their predicted $t_{\text{jet}}$, to compare this distribution to the pre-Swift $E_\gamma$ distributions found by Frail et al. (2001) and Bloom et al. (2003). We do this by utilizing the 25 GRBs in our sample that overlap with the GRBs examined by Panaitescu (2007). In this subset, 13 events with redshift were determined to harbor breaks consistent with the standard jet models, and another 12 were consistent with “potential” jet breaks. Neither the jet break time or the prebreak or postbreak decay indices were reported by Panaitescu (2007) for the events with potential jet breaks, so we utilize the Bayesian blocks algorithm described in §2.2 to measure all three quantities. The resulting fit parameters are displayed in Table 2.

The resulting post-Swift $E_\gamma$ distribution in comparison to the pre-Swift $E_\gamma$ distribution is shown in Figure 6. The median of the post-Swift distribution, as determined through the use of all 25 GRBs, is roughly $9.0 \times 10^{49}$ ergs with a variance of 0.90 dex. The median jet break time for the entire sample is $\log t_{\text{jet}} \sim 4.73$ days. The peak of the post-Swift $E_\gamma$ distribution is much broader and roughly an order of magnitude lower than the distribution derived from the pre-Swift observations. A K-S test returns a probability of $p = 5.66 \times 10^{-3}$ that the pre-Swift and post-Swift distributions are drawn from the same parent population. The lower and upper limits on $E_\gamma$ for all events which show no sign of any breaks in their afterglow light curves are represented as horizontal bars in Figure 6. The last 3 $\sigma$ detection of the XRT sets the lower bound, whereas the upper bound is set to equal the burst’s isotropic equivalent energy $E_{\text{iso}}$. In contrast to the 25 events with breaks in their light curves, the events with no breaks begin to push the post-Swift $E_\gamma$ distribution to higher energies in comparison to the pre-Swift distribution. Two significant outliers (GRB 050820A and GRB 061007) in particular have resulting lower limits to their energies that are above $10^{52}$ ergs.

4. DISCUSSION

The results presented in the previous section paint a complicated picture for GRB energetics in the Swift era. The combination of more distant events and a wider distribution in the observed isotropic equivalent energy has resulted in a much broader $E_\gamma$ distribution for Swift-detected GRBs. The breaks that do exist in the X-ray light curves of many events are typically inconsistent with standard jet model predictions and occur earlier than the pre-Swift jet break distribution. Their application as jet breaks yields an underluminous $E_\gamma$ distribution that is highly inconsistent with the pre-Swift sample.

It may be the case, as also suggested by Panaitescu (2007), that a significant fraction of these potential jet breaks are actually associated with some mechanism other than jet collimation, such as the cessation of late-time energy injection (Rees & Mészáros 1998). The events which have postbreak decay indices $\alpha_2$ that are shallower than the $-1.5$ expected from standard jet models tend to have shallower breaks when compared to the rest of the sample. The median difference between the prebreak and postbreak decay indices for these bursts is roughly $\Delta \alpha \sim 0.48$ compared to that of bursts that have model-consistent jet breaks, which have $\Delta \alpha \sim 1.04$. Second, the distribution of $\alpha_2$ for the events with model-consistent jet breaks is fully consistent with the decay indices exhibited by events which have no breaks in their light curves, as shown in Figure 7. This could indicate that some of these observed breaks may be due to the end of the plateau phase that has become ubiquitous in Swift X-ray light curves (Nousek et al. 2006) and that the true jet break had not been observed by the end of the XRT observations.
Swift E breaks in their light curves are shown as a histogram with lines at +45. Breaks consistent with model predictions (histogram with lines at −45°). The final decay indices for the events which show no breaks in their light curves are shown as a histogram with lines at +45°.

Liang et al. (2007) have recently completed an extensive analysis of the plateau phases observed in XRT light curves and found that the distribution of transition times to a steeper decay is centered at log $t_b = 4.09 \pm 0.61$ s and that the distribution of power-law indices during the phases peaks at $\alpha_1 \sim 0.35 \pm 0.35$. This is in comparison to the median jet break time of log $t_{\text{jet}} = 4.72 \pm 0.60$ and a prebreak power-law index distribution of $\alpha_1 \sim 0.82 \pm 0.23$ for model-inconsistent jet breaks in our Swift sample. Although the distribution of prebreak decay indices is higher than the distribution of plateau decays reported by Liang et al. (2007) it may still be the case that some of the events in our sample consist of light curves with plateau breaks which are steep enough and occur at the upper end of the $t_b$ distribution such that they could be considered as jet breaks which do not conform entirely to standard jet models.

If we exclude GRBs with X-ray breaks that have postbreak decay indices shallower than $\alpha \sim 1.5$, we receive a median post-Swift $E_\gamma \sim 1.12^{+0.38}_{-1.09} \times 10^{39}$ ergs with a variance of 0.65 dex. The removal of these events eliminates the low-energy tail from the post-Swift $E_\gamma$ distribution, making it more consistent with the optically determined pre-Swift energetics distribution, but the distribution is still an order of magnitude lower than the $E_\gamma$ distribution estimated from pre-Swift GRBs. The resulting post-Swift distribution, in comparison to the pre-Swift distribution, is shown in Figure 8. If we assume that these shallow breaks were due to some mechanism other than jet collimation and that the true jet breaks had not yet manifested by the end of the XRT observations, then we can place upper and lower limits on their collimation-corrected energy. These limits are again represented as horizontal bars in Figure 8. Much like the events with no detected jet breaks, the limits on $E_\gamma$ for many of these shallow break events are well above the pre-Swift $E_\gamma$ distribution, pushing the upper end of the post-Swift energy distribution well beyond $10^{42}$ ergs.

We note that all of the pre-Swift $E_\gamma$ estimates that we have used in this analysis come from jet breaks detected in the optical whereas our sample is limited entirely to X-ray wavelengths. There is evidence (Panaitescu et al. 2006; Perley et al. 2008; Curran et al. 2007; Oates et al. 2007) to suggest that the X-ray and optical emission may not evolve achromatically at late times as predicted by blast wave models (Mészáros & Rees 1997; Sari et al. 1998; Panaitescu & Kumar 2000). Many of the various light-curve phases observed in the X-ray do not always manifest at optical wavelengths, indicating that the X-ray and optical emission may originate from distinct and separate physical components. Such a two-component model has been proposed by Kumar & Granot (2003), in which the X-ray and optical emissions originate from two distinct jets of differing degrees of collimation. This model has been invoked by Panaitescu et al. (2006) and Oates et al. (2007) to explain breaks observed in the X-ray light curves of several events which show no such behavior at optical wavelengths. In the context of the two-component jet model, the X-ray break would be due to a narrow central jet and the optical from a wider jet which presumably would cause a break at a much later time. Alternatively, Panaitescu (2008) has suggested that the various components in many X-ray light curves may originate from the scattering of forward shock photons by a relativistic outflow behind the leading blast wave. Under the right conditions, these boosted photons could be more luminous than the X-ray flux of the forward shock itself. In either case, all of the $E_\gamma$ values determined through the use of X-ray breaks become suspect and may not reflect the overall energy budget of the GRB.

These considerations would lead to two possible, albeit conflicting, scenarios. First, that the true $E_\gamma$ distribution of long GRBs is indeed narrowly clustered about a few times $10^{51}$ ergs as the pre-Swift optical data would suggest but that the breaks seen at X-ray wavelengths are unrelated to jet collimation. In this case, a majority of the optical breaks would have to occur well beyond ∼1 day. We find that the median expected jet break time for the Swift sample, given a standard energy of $E_\gamma \sim 1.23 \times 10^{33}$ ergs, is roughly $t_{\text{jet}} \sim 10$ days, considerably beyond the duration, and indeed capability, of most observing campaigns. In this case, only 32% of the Swift sample with known redshift have XRT observations that extend beyond their expected $t_{\text{jet}}$. This scenario would then require some mechanism which could essentially mask the effects of jet collimation at X-ray wavelengths for the events which show straight power-law decays to late times.

Even if we dismiss the assumption that the achromaticity of jet breaks extends to X-ray wavelengths, there still appear to be
events that challenge the notion of a narrow $E$, distribution even at optical wavelengths. The well-studied GRB 061007 has an expected jet break at $\sim 0.18$ days but yet exhibits a single power law at optical wavelengths out beyond 1 day, resulting in a lower limit of $E_\gamma \sim 1.5 \times 10^{52}$ (Schady et al. 2007). Likewise, four events (GRB 050416A, GRB 051016B, GRB 060428B, and GRB 060512) have $E_{\text{iso}}$ values that are below $10^{53}$ ergs, meaning any break in their optical light curve would make the inferred energy released by these events even more inconsistent with pre-Swift estimates.

This leads to the second scenario, in which the jet breaks are indeed seen in some X-ray light curves but long cosmological GRBs have a much wider distribution of $E$, than pre-Swift GRBs would suggest. A wider $E_\gamma$ distribution has already been suggested by low-energy events such as XRFs and SN-GRBs, and there is no a priori reason to believe that the gamma rays, which represent such a subdominant fraction of the entire energy in the collapsar model, should necessarily be standard among all events. It could then still be the case that some the breaks seen in the X-ray wavelengths could be due to jet collimation while others may be manifestations of other mechanisms that only effect the resulting X-ray emission.

In this case, the disparity between the pre- and post-Swift energetics distributions would imply a significant bias toward the detection of jet breaks in bright, relatively nearby GRBs in the pre-Swift era. The effects of such a bias to begin to appear to be significant in Figure 9, where $E_{\text{iso}}$ is plotted versus redshift for all pre- (dark gray) and post- (black) Swift events, including long, short, and SN-associat GRBs. The events for which jet breaks were detected in the pre-Swift sample are plotted in light gray and represent the brighter fraction of the distribution. Furthermore, the presence of multiple light-curve breaks and the long delay between the GRB and subsequent optical and X-ray observations prior to the Swift mission may have also allowed for a bias toward the selection of the last break in a multibreak light curve as the potential jet break. This would have essentially created an artificial lower limit on the pre-Swift $E_\gamma$ distribution.

Ultimately, more contemporaneous observations at optical and X-ray wavelengths will be needed to determine which fraction of the X-ray breaks are truly achromatic. Observing more jet breaks at optical wavelengths would also allow for a direct comparison between the pre- and post-Swift energetics distribution, hopefully eliminating the ambiguity involved with using jet break times determined at different wavelengths. This will require continued interest by the GRB community in obtaining deep optical and/or IR imaging of afterglows several days or even weeks after the initial explosion. Such observations will prove crucial in resolving many of these questions regarding the collimation and energetics of GRBs.

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