Swift X-ray Afterglows: Where are the X-ray Jet Breaks?

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Summary. — We examine the Swift/X-ray Telescope (XRT) light curves from the first ∼150 gamma-ray burst (GRB) afterglows. Although we expected to find jet breaks at typical times of 1-2 days after the GRB, we find that these appear to be extremely rare. Typical light curves have a break in the slope at about $10^4$ s, followed by a single power-law decay whose slope is much too shallow to be consistent with expectations for jet breaks. X-ray light curves typically extend out to ∼10 days without any further breaks, until they become too faint for the XRT to detect. In some extreme cases, light curves extend out to more than two months without evidence for jet breaks. This raises concerns about our understanding of afterglow and jet dynamics, and of GRB energetics.

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1. – Introduction

The beaming factors of Gamma-Ray Bursts (GRBs) are critically important for understanding their overall energetics. For GRBs at known redshift, the GRB fluence can be converted to a total radiated energy assuming isotropic radiation. The values found for $E_{\gamma,iso}$ can range up to $10^{54}$ ergs, a value that is difficult to explain unless the radiation is actually concentrated into a narrow beam, or jet, pointed towards us. The jet beaming factor must then be measured in order to determine the actual beamed energy radiated by the GRB.

Fortunately, the jet opening angle can be determined directly from detailed measurements of the light curves of GRBs. The power law decay indices of GRB afterglows are expected to steepen to $F_\nu \propto t^{-p}$ when the jet has decelerated to the point that the bulk Lorentz factor, $\Gamma$, is given by $\Gamma \sim \theta_j^{-1}$, where $p$ is the power law index of the electron energy distribution and $\theta_j$ is the opening angle of the collimated jet \[ \frac{\Gamma}{\theta_j} \]

\[ \theta_j = \frac{1}{6} \left( \frac{t_j}{1+z} \right)^{3/8} \left( \frac{m_{\gamma}}{E_{\gamma,iso,52}} \right)^{1/8}, \]

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where $\theta_j$ is the jet opening angle in radians, $t_j$ is the jet break time in days in the observer’s frame, $n$ is the ambient number density in cm$^{-3}$, $\eta_\gamma$ is the radiation efficiency, and $E_{\gamma,\text{iso},52}$ is the isotropic equivalent energy radiated in gamma rays in units of $10^{52}$ erg$^{-1}$. Without broad-band data, including radio observations, fitted to a detailed afterglow model, we cannot in general determine the density or efficiency for a given burst, and only some 10% of bursts have radio detections. Furthermore, the redshift is known for only $\frac{1}{3}$ of bursts with XRT observations. We therefore rewrite Eq. 1 in terms of typical values for the unknown parameters, as

$$\theta_j = 0.064 \xi t_j^{3/8},$$

where we define

$$\xi \equiv \left( \frac{3.5}{1+z} \right)^{3/8} \left( \frac{\eta_\gamma}{0.2} \right)^{1/8} \left( \frac{n}{E_{\gamma,\text{iso},53}} \right)^{1/8}. \quad (3)$$

For typical values of $z \sim 2.5$ (the mean redshift for long Swift bursts), $\eta_\gamma \sim 0.2$, $n \sim 1$ cm$^{-3}$, and $E_{\gamma,\text{iso}} \sim 10^{53}$ ergs, we have $\xi \sim 1$. The dependence of $\xi$ on $\eta_\gamma$, $n$, and $E_{\gamma,\text{iso}}$ is very weak.

The “jet break” should be independent of energy, with an achromatic break time and the same post-break decay index, $p$, for all frequencies. Several observational studies based primarily on breaks in optical and radio light curves [2, 3] have reported that jet breaks of long GRBs typically occurred a few days after the burst, with typical jet angles of $5^\circ - 10^\circ$, and showed that the $\gamma$-ray energies, corrected for the jet collimation, are tightly clustered around $10^{51}$ ergs. This implies a regulating mechanism that produces similar radiation output from events thought to originate from the gravitational collapse of massive stars of widely varying mass, and raises the possibility that GRB afterglows may be of cosmological use as “standard candles”. However, X-ray light curves from Swift do not exhibit similar behavior. We review the observational situation regarding the X-ray light curves and discuss the implications.

2. X-ray Jet Breaks observed by the XRT

As of 7 October 2006, the X-ray Telescope (XRT) [4] on the Swift satellite [5] had observed 145 “long” GRBs and 16 “short” GRBs. The XRT detected 143 of the “long” bursts and followed their afterglows until they faded into the background, typically at a count rate of $\sim 5 \times 10^{-4}$ s$^{-1}$. We consider the sample of 147 of these X-ray light curves collected by the Swift XRT between 1 April 2005 and 7 October 2006. Prior to 1 April 2005 Swift was primarily collecting calibration data, and afterglow observations extending past a few days were generally not possible. Long-term monitoring of X-ray afterglows became common once normal operations started. This data set provides the most detailed, uniform sample of GRB afterglows available, with observations usually lasting for at least several days and often for several weeks after the burst, far longer than the slope changes attributed to jet breaks in earlier works. One surprise has been the paucity of jet breaks in these X-ray light curves. Based on previous work [2, 3], we had expected typical X-ray light curves to break at $\sim T_0 + 1$ day to $\sim T_0 + 4$ days to a steeper fall-off of $\alpha \sim 2.0 - 2.5$. This behavior is rarely seen in the X-ray light curves from Swift. While steepening breaks are seen in the X-ray light curves, they usually occur at $\sim 0.1$ days post-burst and break to slopes typical of pre-jet break (spherical) afterglows,
and at least some of these are not accompanied by similar breaks in the optical \[6\]. It seems unlikely that these early breaks can be attributed to jet breaks, and they have instead been attributed to the end of an energy injection phase that often causes a flat “plateau” in the X-ray light curves at typical time scales of several hundred seconds \[7\].

Two examples of XRT light curves with possible jet breaks are shown in Figure 1. Both of these bursts show all of the X-ray light curve segments that are now recognized as “canonical” \[7\], although very few GRBs actually present all of these phases. The light curves can be represented as a series of broken power laws with superimposed flares, with each segment described by a decay slope $\alpha_x$ given by $F_x \propto t^{-\alpha_x}$. The slope during the spherical expansion part of the light curve is typically $\alpha_x \sim 1.3$ with considerable scatter. The slope following the jet break is expected to be $\alpha_x = p \sim 2.5$, again with considerable scatter. The bursts shown in Fig. 1 have final slopes $\alpha_x \sim 2.1$ and 1.8, consistent with jet breaks. While the break time for GRB 050315, about 2.8 days, is typical of previously reported jet break times, the break found in GRB 060428A, at $\sim 10.3$ days after the burst, is somewhat later than most previously reported jet breaks.

Two more potential jet breaks are shown in Fig. 2. GRB 050814 breaks from a shallow plateau phase with $\alpha \approx 0.8$ to a post-break slope of 1.9. Like GRB 050315, the break occurs in the expected time-frame based on previous work: about 1.0 days in the observer frame in this case (though with a redshift of $z = 5.3$ \[9\] this break occurs at only 13 ks in the GRB rest frame). For $E_{\gamma, iso} \sim 1.8 \times 10^{53}$ (Sakamoto, private communication), we obtain a jet angle of $\theta_j \sim 3^\circ \ n^{1/8}$ from Eq. 1 (for $\eta_\gamma = 0.2$). GRB 060614 is one of the best examples of a Swift burst with a jet break, having an achromatic break at about 1.3 days in both X-ray and optical bands, and breaking to a slope of $\sim 2.2$ \[10\]. We estimate a jet angle for this burst of about $10^\circ \ n^{1/8}$, and $E_\gamma \sim 3.6 \times 10^{49}$ erg. It is not clear whether this burst is a subluminous “long” GRB with no SN component \[11-14\] or a highly energetic “short” GRB \[15\].

3. Long-term X-ray afterglows without jet breaks

X-ray light curves with jet breaks, however, are decidedly in the minority. In a detailed study of 107 X-ray afterglow light curves \[16\], only a few percent are found that satisfy the closure relations between the decay slope and the spectral slope expected for post-jet
break light curves (e.g. [17]). The vast majority have no evidence for a break in the light curve with the characteristics expected for jet breaks. To illustrate the problem, we present examples of X-ray light curves of GRBs with long observation times. Although this is a small sample of a much larger collection of X-ray light curves, these are typical of the overall group. We make the assumption that the jet break occurs after the last data point in these cases.

We begin with the X-ray light curve of GRB 050401 (Fig. 3). Although this light curve has several large gaps, it extends to about 800 ks with no evidence for any break after about 7 ks. The final break in the light curve is at 4.9 ks, and the final slope is $1.46 \pm 0.07$ [18]. This is a typical slope for a spherically-expanding afterglow, but is far too shallow to satisfy the closure relations for the post-jet break case [18]. We conclude that any jet break must occur after $\sim$ 800 ks. With a redshift of 2.9 and $E_{\text{iso}} = 3.5 \times 10^{53}$ ergs [18], we find a lower limit on the opening angle of $\theta_j > 7^\circ n^{1/8}$. Because of the relatively large redshift and high isotropic energy, this rather late limit to a jet break time is compatible with typical opening angles from [2, 3].

GRB 050416A (Fig. 4) puts very strong constraints on a jet break time. This burst has one of the longest afterglow followups to date with the Swift/XRT, with observations continuing for 74 days after the burst [19]. With more sensitive reanalysis of this light curve, we detect the afterglow up to 70 days post-burst, with a slope of $\alpha = 0.9$ from 1.45 ks to 6 Ms (Fig. 4). This is somewhat flatter than expected for a spherical afterglow ($\alpha \sim 1.1$ for this case). Using Eq. (1), we find that $\theta_j > 42^\circ n^{1/8}$.

GRB 050607 (Fig. 5) has a typical XRT light curve, with strong flares at early times, a plateau phase, and then a normal afterglow phase extending until 1.7 Ms post-burst, when it becomes undetectable. This last phase has a slope of $\alpha = 1.1$ and fits the closure relation expected for a standard afterglow propagating into a uniform density ISM, with electron index $p \sim 2.2$ [20]. The redshift is not known for this burst, so the jet angle cannot be determined directly. We use Eq. 2 to obtain an estimate of $\theta_j > 11^\circ \xi$.

GRB 050803 (Fig. 6) has a somewhat erratic light curve. After $\sim$ 15 ks the light curve breaks to a slope of $\alpha = 1.7$, with considerable scatter that may represent small flares superimposed on the afterglow. This slope continues for about 13 days post-burst, giving
WHERE ARE THE X-RAY JET BREAKS?

Fig. 3. – Swift/XRT light curve of GRB 050401. The final break in the X-ray light curve is at about 4.9 ks, to a final decay slope of 1.5 [18], typical for a normal “spherical” (pre-jet break) afterglow and much flatter than expected for a post-jet break light curve.

us an estimate for the jet opening angle of \( \theta_j > 10^\circ \xi \).

GRB 050822 (Fig. 7 [21]) has flares at early times, a very flat plateau phase, and a standard decay after \( \sim 15 \) ks with a slope \( \alpha = 1.1 \). There is no evidence for a jet break before 52 days post-burst. This burst has no optical counterpart and hence no redshift measurement, but [21] show that such a late break is unexpected for any redshift less than 10. We find a jet angle of \( \theta_j > 16^\circ \xi \) for this afterglow.

Fig. 4. – Swift/XRT light curve of GRB 050416A [19]. The final break in the light curve is at about 1.5 ks, to a final decay slope of 0.9, a bit shallow for a normal afterglow, and far flatter than expected for a post-jet break light curve.

Fig. 5. – Swift/XRT light curve of GRB 050607 [20]. The final break in the light curve is at about 8 ks, to a final decay slope of 1.1.

Fig. 6. – Swift/XRT light curve of GRB 050803. The final break in the light curve is at \( \sim 13 \) ks, to a final decay slope of 1.7.
One can infer a plateau phase for GRB 051109A (Fig. 7) during the first orbital gap, followed by a simple power law decay with $\alpha = 1.2$ until 16 days post-burst, with low-level flaring superimposed on the power law decay. This burst has a redshift of 2.346 [22] and $E_{\text{iso}} = 5 \times 10^{52}$ ergs [23], from which we can determine a minimum opening angle of $\theta_j > 12^\circ n^{1/8}$.

GRB 051117A (Fig. 8 [24]) and GRB 060202 both have long light curves, beginning with substantial flaring and then settling down to simple power law decays at late times. Both GRBs have a rather flat final decay slope of 0.9 from $\sim 10^4$ s until the afterglow becomes undetectable by the XRT. The afterglow continues until $\sim 20$ days post-burst for 051117A, and until $\sim 29$ days post-burst for 060202. Neither burst has a redshift measurement, so we use Eq. 2 to estimate their jet angles as $\theta_j > 11^\circ \xi$ for 051117A and $\theta_j > 13^\circ \xi$ for 060202.
WHERE ARE THE X-RAY JET BREAKS?

Fig. 9. – Left: Optical light curve of GRB 060206 (from [26]). There is a clear break in the optical light curve at \( \sim 60 \) ks. Right: Swift/XRT light curve of GRB 060206. Although the data are somewhat “noisy”, perhaps due to small-scale flaring, there is no evidence of any break in the X-ray light curve after \( \sim 5 \) ks (until it flattens out at about \( 10^6 \) s). The dashed line indicates the X-ray light curve expected if the optical break at \( \sim 60 \) ks were achromatic, and is clearly a poor fit to the late data.

We next consider GRB 060206 (Fig. 9), a high redshift burst with \( z=4.048 \) [25] and \( E_{\gamma,iso} = 5.8 \times 10^{52} \) ergs [28]. This burst had a bright, particularly well-sampled optical light curve for the first two days of the afterglow [26, 27]. The optical light curve breaks from a slope of \( \alpha_o = 0.95 \pm 0.02 \) to a steeper slope of \( 1.79 \pm 0.11 \) at a time of \( \sim 30-90 \) ks [26]. This break is interpreted as a jet break by [27], who overplot the X-ray light curve from 60 s to 230 ks on the optical light curve, normalized so that the highest points on the X-ray light curve match the optical light curve in the interval 5-40 ks. Over this limited range, with the large scatter in the X-ray data points, the X-ray and optical light curves agree reasonably well, which [27] claim as evidence that the X-ray light curve follows the optical light curve. This would imply that the break in the optical light curve is achromatic. However, examination of the entire X-ray light curve makes it clear that there is no evidence for any change in the overall X-ray slope of \( \sim 1.3 \) between 5 ks and at least 15 days post-burst (Fig. 9; from 15 days to 26 days the light curve is flat, after which the source became undetectable). Furthermore, we note that variability in X-ray light curves of the sort seen in this light curve is fairly common, and it is likely to be due to mini-flares superimposed on a relatively smooth underlying afterglow. This variability, combined with the large uncertainties in the X-ray data points, can account for the apparent agreement between the optical and X-ray light curves over the small time interval considered by [27]. We conclude that the optical break is a chromatic break unassociated with a jet break, in agreement with [20]. In our interpretation, the X-ray light curve is unbroken from 5 ks to at least 1.3 Ms, or 15 days post-burst. We derive a limit of \( \theta_j > 10^\circ n^{1/8} \) for the jet opening angle.

GRB 060319 is another exceptionally long X-ray light curve, extending to 42 days post-burst (Fig. 10). The initial decay slope is \( \sim 1.2 \), though with significant variability, from 230 s to 8 ks. Between 8 ks and 18 ks there is an episode of energy injection into the external shock, after which the afterglow resumes a steady decay slope of \( \alpha = 1.2 \) that continues until 1.3 Ms, with a very late flare or energy injection episode followed by a continuing decay until 3.6 Ms. This afterglow has no optical counterpart or redshift. We estimate the jet break opening angle to be \( \theta_j > 15^\circ \xi \).
GRB 060729 has the longest X-ray afterglow seen to date by *Swift*, decaying at a slope of \( \alpha = 1.4 \) for over 10 Ms [29] (\( \sim 81 \) days in the GRB rest frame!). Fig. 11 shows the first 5 Ms of the light curve. The object was unusually bright when the observation began. A typical steep decay with a strong flare was followed by an extremely flat, unusually long plateau phase extending to \( \sim 60 \) ks. The final decay slope is typical for a pre-jet break spherical outflow. With a redshift of \( z = 0.54 \) [36] and \( E_{\gamma,\text{iso}} = 1.6 \times 10^{52} \) ergs, we find \( \theta_j > 38^\circ \theta_1^{1/8} \) for this afterglow.

The light curve of GRB 060814 (Fig. 12) is rather similar to that of 060729, with the same final slope. But because 060814 is somewhat fainter to begin with and has a much shorter plateau phase ending ten times sooner at about 7 ks, the afterglow was only detectable by XRT for about 15 days. With no redshift, we estimate the jet opening angle to be \( \theta_j > 10^\circ \xi \).

As our final example, we consider GRB 061007 (Fig. 13 [30]). Unlike most XRT light curves, the X-ray light curve of 061007 has no breaks, decaying as a single power law of slope \( \alpha = 1.66 \) from \( \sim 80 \) s to \( \sim 1.1 \) Ms. This object is also unusual in that the bright, well-sampled optical light curve has exactly the same slope as the X-ray light curve shown here. If we interpret this burst as being a pre-jet break decay, the opening angle is \( \theta_j = 8^\circ \theta_1^{1/8} \). However, detailed consideration of the afterglow model leads to the conclusion that it is difficult to produce a model that satisfies the optical and X-ray observations unless the entire observed light curve is post-jet break [30]. This would require a jet break at \( t_j < 80 \) s for this burst, with a resulting jet angle \( \theta_j < 1^\circ \) [30]. This solution, however, also has difficulties, as the decay slope is shallower than expected for a post-jet break decay of a uniform jet and does not satisfy the post-jet break closure relations. One solution is a very steady energy injection phase lasting over the entire duration of the observed afterglow, but it is hard to imagine how this can be produced. Alternatively, it is possible that this burst can be explained by a structured jet model [31]. GRB 061007 raises some interesting questions about the time-scale of the jet breaks as well as our “standard” interpretations of detailed X-ray and optical light curves.
WHERE ARE THE X-RAY JET BREAKS?

4. Cases of Perplexing Breaks

We now consider two cases of light curve breaks that may be jet breaks, but that do not seem completely compatible with the expectations of the standard afterglow models. Like GRB061007, these raise interesting questions about our detailed understanding of GRB afterglows.

GRB050525A (Fig. 14) is another case with good X-ray and optical light curves [32]. There is a shallow break in the X-ray light curve at 13 ks to a final slope of $\alpha = 1.6$, much flatter than expected for a post-jet break decay.

GRB060814, showing the typical decay phases: rapid decline with flares, plateau, and power-law decay with slope of $\alpha \sim 1.4$, with some late-time flares superimposed.

Fig. 12. – Swift/XRT light curve of GRB060814, which consists of a single power-law decay ($\alpha = 1.66$) for over 1 Ms.

Fig. 13. – The unusual Swift/XRT light curve of GRB061007 [30], which consists of a single power-law decay ($\alpha = 1.5$).

Fig. 14. – Swift/XRT light curve of GRB050525A [32].

Fig. 15. – Swift/XRT light curve of GRB060124 [33]. The final break in the light curve found by [33] is at about 100 ks to a final slope of $\alpha = 1.5$, though we find a single late slope fits our light curve.
The very early X-ray decay has some low-level flaring (not shown here), followed by a two-slope decay with a shallow break from $\alpha_1 = 1.20$ to $\alpha_2 = 1.62$, with a break time of 13.7 ks [32]. There is a break in the optical light curve at the same time, making this the first achromatic break observed across both optical and X-ray bands, and this has therefore been interpreted as a jet break with opening angle $\theta_j = 3^\circ$ [32]. Before this break, the data are in good agreement with the standard fireball model for an external shock propagating into a constant density ISM. The final decay slope is considerably flatter than expected for a jet break, however, and does not satisfy any of the closure relations, either pre-jet break or post-jet break. If this is indeed a jet break, it requires some additional component or tweaking of the standard models (such as structured jets) to obtain a completely self-consistent interpretation.

GRB 060124 (Fig. 15; [33]) is a fascinating burst. The Swift satellite triggered on a precursor nearly 10 minutes before the main burst, which was therefore observed by the XRT and UVOT instruments, producing one of the most detailed broad-band observations of prompt emission ever made [33]. Here, we consider the long-term X-ray light curve. [33] found that the X-ray light curve of 060124 after $10^4$ s is very similar to that of 050525A, with a decay slope of $\alpha = 1.2$ from $10^4$ to $10^5$ s, followed by a steeper decay with slope $\alpha = 1.5$. Like 050525A, the data before the break are in good agreement with a standard fireball model for a constant density ISM [33], but after the break the decay is much too shallow for a standard post-jet break model. The data may be consistent with a structured jet model, which can accommodate a flatter post-break decay slope [33]. On the other hand, we find a reasonably good fit to a single power law (Fig. 15) with small-scale flaring.

5. – Short GRBs

Finally, we note that jet breaks have been proposed or investigated for several short GRBs [34, 35, 37]. The best observations to date are for GRBs 050724 [35] and 051221A [37]. Late Chandra observations of GRB 050724 are consistent with a slow afterglow decay with $\alpha \sim 0.9$ extending without a break until 22 days after the burst, resulting in an estimate of $\theta_j > 25^\circ$ for an ambient density of $n = 0.1$ cm$^{-3}$ [35] and an isotropic energy of $E_{\gamma,iso} = 4 \times 10^{50}$ ergs [38]. By contrast, late Chandra observations of GRB 051221A clearly show a jet break at $t_j \sim 4$ days post-burst, breaking to a decay slope of $\alpha \sim 1.9$. Fitting the X-ray data, along with optical and radio data [39], to a detailed fireball model, a jet opening angle of $\theta_j \sim 4^\circ - 8^\circ$ is obtained [37]. The results suggest that short GRBs can have a wide range of collimation angles.

6. – Discussion

We summarize the observational details discussed above in the following tables, which also include a few cases not discussed above. Table 1 gives jet parameters for bursts with possible jet breaks. These are typically given in terms of the density dependence, since we generally do not have good estimates for densities, and assume a radiation efficiency of 0.2. For comparison, [2] assumed $n = 0.1$ cm$^{-3}$, while [3] use density estimates from detailed afterglow modelling when possible (these range from 0.1-30, but are typically on the high side of this range), choosing a “canonical” value of 10 cm$^{-3}$ when no modelling-based estimate was available. In the case of GRB 060428A, which has no redshift measurement, we characterize the opening angle in terms of $\xi$ (see Eq. 3), which we expect to be of order 1. Table 2 gives similar parameter estimates for the bursts with no apparent jet break.
In this case, we take the break time to be larger than the time of the last observation, and derive corresponding estimates of the jet opening angle and energetics. When no redshift is available, we again characterize the opening angle in terms of $\xi$.

The results are rather interesting. For the few potential jet breaks, the distribution of opening angles is similar to those of $\Theta$ [2, 3] (typically $5^\circ - 10^\circ$), given the small sample size. Not surprisingly, the lower limits found for the cases without breaks tend to be considerably higher, consistent with the much larger break times inferred for most of these cases. Although this could be partially the result of time dilation due to the higher redshifts in the Swift sample compared with earlier studies, this cannot be the entire story. The average redshift of our sample is only about twice that of the earlier studies, and the ratio of time dilation factors ($\sim 1.3$) cannot explain the much later times we find for jet breaks. Interpreting the early X-ray light curve breaks as jet breaks does not seem to be a general solution to the lack of jet break observations, since the slope following these early breaks tends to be consistent with the standard pre-jet break afterglow models. We are still left with the puzzle: where are the X-ray jet breaks?

We can consider whether the lack of redshifts is somehow biasing our results. Comparison of the jet angle limits in Table 2 for bursts with and without redshift measurements shows that the limits are similar: the jet limits for bursts without redshifts are typically about $13^\circ$, very similar to the median lower limit for those bursts with redshift measurements (though in the latter sample we have two bursts with much higher jet angles). We conclude that there is no evidence that the jet angle limits for bursts without redshifts differ from those with redshifts.

The lower limits to jet angles for bursts without observed jet breaks are typically about a factor of two higher than the jet angles found for bursts with jet breaks around a few days. If these populations are the same, we can reconcile these results by assuming a smaller density for the bursts without breaks. Because the dependence of $\theta_j$ on $n$ is so weak, very low densities are required, with $n \sim 4 \times 10^{-3}$ cm$^{-3}$, typical of densities expected in a hot phase of the ISM. Alternatively, the radiation efficiency could be much lower than the value of 0.2 assumed in Table 2: this would require $n_\gamma \sim 10^{-3}$ for these bursts.

Within the context of the standard jet break model (for a uniform jet), we therefore must consider the possibility of a bimodel distribution of either density or efficiency. We note that a bimodal density distribution might in principle be able to explain why bursts

| GRB     | Jet break time (days) | Final $\alpha$ | $z$  | $E_{\gamma,iso,52} (10^{52}$ ergs) | $\theta_j$ (deg) | $\log(E_\gamma)$ (ergs) | Ref |
|---------|-----------------------|----------------|------|----------------------------------|------------------|------------------------|-----|
| 050315  | 2.8                   | 2.1            | 1.949| 3.3$^\dagger$                    | $7 n^{1/8}$      | 50.3                   | [8] |
| 050814  | 1.0                   | 1.9            | 5.3  | 18                               | $3 n^{1/8}$      | 50.3                   |      |
| 050820A | 14.5                  | 2.2            | 2.612| 83                               | $8 n^{1/8}$      | 51.9                   | [10]|
| 051221A$^a$ | 4.1               | 1.9            | 0.546$^b$| 0.15$^b$                          | 4–8              | 48.9                   | [37]|
| 060428A | 9.4                   | 1.8            | 0.125| 0.25                             | $10 n^{1/8}$     | 49.6                   | [10]|
| 060614$^{a,b}$ | 1.3               | 2.2            | 0.125| 0.25                             | $10 n^{1/8}$     | 49.6                   | [10]|

$^a$ Short GRB  
$^b$ from [39]  
$^c$ See Eq. 3 for definition of $\xi$  
$^\dagger$ Over the 15-150 keV band in the observer’s frame (from [8]), instead of the typical bolometric bands typically used. This probably underestimates the jet angle.
Table II. – Jet limits for GRBs with no jet breaks: upper limits assume $t_j > t_{\text{final}}$.

| GRB     | Last Break time (ks) | Final $\alpha$ | Final data point (days) | $z$ | $E_{\gamma,\text{iso,52}}$ ($10^{52}$ ergs) | $\theta_j$ (deg) | \(\log(E_\gamma)^\dagger\) (ergs) |
|---------|----------------------|----------------|-------------------------|-----|---------------------------------------------|------------------|-----------------------------------|
| 050401  | 4.9                  | 1.46           | 9                       | 2.9 | 35                                          | > 7 $n^{1/8}$     | > 51.4                            |
| 050416A | 1.5                  | 0.88           | 71                      | 0.654 | 0.12                                      | > 42 $n^{1/8}$    | > 50.5                            |
| 051109A | $< 3$                | 1.2            | 16                      | 2.345 | 5                                          | > 12 $n^{1/8}$    | > 51.0                            |
| 060206  | $< 5$                | 1.3            | 15                      | 4.048 | 5.8                                        | > 10 $n^{1/8}$    | > 50.9                            |
| 060729  | $\sim 60$           | 1.4            | 125                     | 0.54  | 1.6                                        | > 38 $n^{1/8}$    | > 51.5                            |
| 061007  | $< 0.08$             | 1.7            | 13                      | 1.26  | 100                                        | > 8 $n^{1/8}$     | > 52.0                            |
|         |                      |                |                         |      | $< 0.3$                                    |                  | < 48.9                            |

\[1\] Radiated energy assuming ambient density of 1 cm$^{-3}$

\[2\] Lower limit for 061007 jet break, assuming $t_j < 80$ s

with bright optical afterglows seem to have earlier jet break times than those found in the X-ray sample: since the cooling frequency is typically between the X-ray and optical bands, the low frequency flux should be density-dependent while the X-ray flux is not. The observations may imply a bimodal ambient density, with low densities for some GRBs (which tend to have very late jet breaks and faint optical counterparts).

The derived beaming-corrected energies for the bursts with breaks are comparable to those found in earlier studies. However, the lower limits on $E_\gamma$ for the bursts without breaks are comparable to the average energies found by [3]. Unless the jet breaks are typically happening just after the end of our observations, the concept of a constant energy reservoir [2] may need to be revisited. Deep observations at very late times are needed to make further progress, and we have an approved Chandra ToO program to begin to address this.

Finally, we reiterate the point that many X-ray afterglows seem to exhibit characteristics that are difficult to accommodate in the standard fireball model. We have shown a number of cases in which the decay cannot be directly reconciled with the expected closure relations. Some of these can be explained by extended energy injection phases, but the mechanism needs to be quite steady, and in the (admittedly extreme) case of GRB061007, needs to extend continuously for over six days in the GRB rest frame. A more plausible solution may lie in structured jets, which could also explain some other cases in which apparent jet breaks are followed by rather shallow decays. On the other hand, similar problems with the standard model have been raised by unexpected chromatic breaks [6] at early times and by the lack of an X-ray break accompanying the optical break in GRB060206. Many of these features can be explained by tweaking the knobs of the fireball model, but one begins to have an uncomfortable feeling that we may be missing something more fundamental that these data are trying to tell us. Perhaps these observations are the clues that will ultimately lead to a better understanding of the underlying physics behind GRB afterglows and the formation of jets during black
hole formation.

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