LATE-TIME DETECTIONS OF THE X-RAY AFTERGLOW OF GRB 060729 WITH CHANDRA—THE LATEST DETECTIONS EVER OF AN X-RAY AFTERGLOW

DIRK GRUPE¹, DAVID N. BURROWS¹, XUE-FENG WU¹,², XIANG-YU WANG¹,³, BING ZHANG⁴, EN-WEI LIANG⁵, GORDON GARMIRE⁶, JOHN A. NOUSEK¹, NEIL GEHRELS⁶, GEORGE R. RICKER⁷, AND MARSHALL W. BAUTZ⁷

¹ Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA; grupe@astro.psu.edu
² Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China
³ Department of Astronomy, Nanjing University, Nanjing 210093, China
⁴ Department of Physics, University of Nevada, Las Vegas, NV 89154, USA
⁵ Department of Physics, Guangxi University, Nanning 530004, China
⁶ Astrophysics Science Division, Astroparticle Physics Laboratory, Code 661, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
⁷ Massachusetts Institute of Technology, 77 Massachusetts Av., Cambridge, MA 02139-4307, USA

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ABSTRACT

We report on five Chandra observations of the X-ray afterglow of the gamma-ray burst (GRB) 060729 performed between 2007 March and 2008 May. In all five observations, the afterglow is clearly detected. The last Chandra pointing was performed on 2008 May 4, 642 days after the burst—the latest detection of a GRB X-ray afterglow ever. A reanalysis of the Swift XRT light curve together with the three detections by Chandra in 2007 reveals a break at $\sim$1.0 Ms after the burst with a slight steepening of the decay slope from $\alpha = 1.32$ to 1.61. This break coincides with a significant hardening of the X-ray spectrum, consistent with a cooling break in the wind medium. The time of this jet break can be used to infer the jet half-opening angle of $\sim 14^\circ$ for a wind medium. Alternatively, this final break may have a spectral origin, in which case no jet break has been observed and the X-ray afterglow of GRB 060729 is such an exceptionally long-lasting event.

Key words: gamma-ray burst; general – gamma-ray burst: individual (GRB 060729)

Online-only material: color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs) are the most energetic transient events in the universe. The most accepted model to explain this phenomenon is the “fireball” model (e.g., Mészáros 2006; Zhang & Mészáros 2004) and the progenitor of long GRBs is believed to be massive stars on the order of 30 solar masses or more. The isotropic energies inferred from the observed fluxes are often of order $10^{53}$–$10^{54}$ ergs. On the other hand, typical supernova explosions are of the order of only $10^{51}$ ergs. One way to solve this “energy problem” is by assuming that the radiation is collimated into a jet. One prediction of the “fireball” model is that the afterglow decay rate increases when the relativistic beaming angle equals or exceeds the physical jet opening angle as the jet decelerates in the surrounding medium (e.g., Rhoads 1999; Sari et al. 1999). This can be seen as an achromatic jet break in the light curve, with a typical decay slope after the jet break of $\alpha = 2$ (e.g., Zhang et al. 2006; Nousek et al. 2006). The time of this jet break can be used to infer the jet opening angle by, e.g., the relation given by Frail et al. (2001). The measurement of the jet break time is therefore most critical for understanding the energetics of GRBs.

Before the launch of the Swift GRB explorer mission (Gehrels et al. 2004), putative jet breaks were found at optical or radio wavelengths, typically a few days after the burst (e.g., Frail et al. 2001). Since its launch, Swift has detected roughly 400 bursts (end of 2008) and typically observed them for up to one or two weeks after the trigger. For the majority of these bursts, jet breaks have not been detected (e.g., Burrows & Racusin 2007; Willingale et al. 2007; Liang et al. 2008; Racusin et al. 2009; Evans et al. 2009). However, one reason could be that jet breaks occur in X-rays at much later times than previously thought and the follow-up observations by Swift are not late enough in time to detect a jet break, as studies by Willingale et al. (2007) and Sato et al. (2007) suggest. As an alternative, Curran et al. (2008) suggested that the jet breaks are hidden and the light curves are mis-interpreted as a single power-law decay, although a jet break is there. Only a handful of afterglows have been followed for more than a month by Swift, because usually the X-ray afterglow fades below the Swift X-Ray Telescope (XRT; Burrows et al. 2005) detection limit $\sim 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ roughly a week after the trigger. One of these exceptions is the bright X-ray afterglow of GRB 060729 which was detected by Swift XRT even 125 days after the burst (Grupe et al. 2007).

The Swift Burst Alert Telescope (BAT; Barthelmy 2005) triggered on GRB 060729 on 2006 July 29, 19:12:29 UT (Grupe et al. 2007) and a redshift of $z = 0.54$ was measured (Thoene et al. 2006). The XRT and the UV Optical Telescope (UVOT; Roming et al. 2005) started observing the burst about two minutes after the trigger. The Swift UVOT was able to follow this afterglow in the UVW1 filter up to 31 days after the BAT trigger. In X-rays, Swift XRT was still detecting the X-ray afterglow of GRB 060729 at the end of 2006 November, 125 days after the burst (Grupe et al. 2007). However, by 2006 December the Swift XRT detection limit was reached and only a $3\sigma$ upper limit could be given for the 63.5 ks exposure time obtained in 2006 December. By that time, the X-ray afterglow of GRB 060729 did not show any clear evidence for a jet break, giving a lower limit...
on the jet opening angle of $\theta = 28^\circ$ (Grupe et al. 2007) based on the assumption of a constant circumburst medium. In order to extend the light curve of this exceptional X-ray afterglow, we observed it 5 times with Chandra ACIS in 2007 and 2008.

We report on the detections of the X-ray afterglow of GRB 060729 (Grupe et al. 2007) with Chandra up to 642 days after the burst—the latest detection ever of an X-ray afterglow of a GRB at cosmological distance. Previously, the burst with the latest detection of an X-ray afterglow was GRB 030329 (Tiengo et al. 2003, 2004), which had a detection 258 days after the burst by XMM-Newton. Our paper is organized as follows. In Section 2 the observations and data reduction are explained; in Section 3 the measurements of the X-ray light curve are shown; and in Section 4 we discuss the implications of this light curve. Throughout this paper, the X-ray flux dependence on time and frequency is defined as $F \propto T^{-\beta} \nu^{-\gamma}$. Luminosities are calculated assuming a $\Lambda$CDM cosmology with $\Omega_M = 0.30$, $\Omega_{\Lambda} = 0.70$, and a Hubble constant of $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$ corresponding to a luminosity distance $d_L = 3064$ Mpc for GRB 060729.

2. OBSERVATIONS AND DATA REDUCTION

Chandra observed GRB 060729 3 times between 2007 March 16 and 2007 June 30. Two very late-time Chandra observations were performed in 2007 December/2008 January for 72.7 ks and in 2008 April/May for 117.3 ks. Due to pitch angle constraints, some of these had to be split into several visits. All observations, with start and end times and exposure times, are listed in Table 1.

All of these observations were performed with the standard 3.2 s readout time in very faint (VF) mode on the on-axis position on the back-illuminated ACIS-S3 CCD. Data reduction was performed with the Chandra analysis software CIAO version 4.0 and the calibration database CALDB version 3.4.3. In order to reduce the ACIS particle background, all Chandra stage-1 event data were reprocessed using CIAO acis_process_events with the VF mode cleaning. Only ACIS grades 0, 2, 3, 4, and 6 were selected for further analysis. The background was further reduced by using only photons in the 0.5–8.0 keV energy range.

Before further analysis, the observations were combined into one event file each using the CIAO task merge_all. Source photons were selected in a circle with a radius $r = 1''$ and background photons in a close-by source-free region with a radius $r = 10''$. Count rates were converted into fluxes by using PIMMS version 3.9b using the parameters from the spectral fits to the Swift data after the break at 1 Ms after the burst (see below) with an absorption column density $N_H = 1.34 \times 10^{21}$ cm$^{-2}$ and $\beta_X = 0.89$.

A description of the reduction and analysis of the Swift data can be found in Grupe et al. (2007). For display purposes and fitting the late-time light curve, we rebinned the Swift XRT Photon Counting data with 250 counts per bin for the times up to 2 Ms after the burst and 100 counts per bin for the times thereafter. Spectral analyses were performed for the times 300–800 ks and $T > 1$ Ms after the burst. Source photons were collected in a circle with $r = 23''5$ and background photons with $r = 96''$ with grade selection 0–12. The response matrix swxpc0to12s0_20010101v010.rmf was used. The spectra were rebinned with 20 counts per bin for the 300–800 ks after the burst spectrum and 15 counts per bin for the spectrum with $T > 1$ Ms. The spectra were analyzed with XSPEC version 12.4.0x (Arnaud 1996). To search for changes in the X-ray spectrum, we applied a hardness ratio study segment by segment. Because of the low-number statistics in some of the later segments of the Swift XRT and all Chandra observations, we applied Bayesian statistics to determine the hardness ratios as described by Park et al. (2006).

3. RESULTS

3.1. Temporal Breaks

The late-time X-ray light curve including the five Chandra pointings is shown in Figure 1. We ignore the first day of the Swift observation because it is not relevant for the study of the late-time light curve. The early light curve and a detailed discussion can be found in Grupe et al. (2007).

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**Table 1**

Chandra Observation Log of GRB 060729

| ObsID  | T-start$^a$ | T-stop$^a$ | $T_{\text{exp}}^b$ | CR$^c$ | $F_{0.3-10.0 \text{keV}}^d$ |
|--------|-------------|-------------|---------------------|--------|----------------------------|
| 7567   | 2007 Mar 16 11:39 | 2007 Mar 16 19:57 | 27690 | 3.93$^{+1.28}_{-0.91}$ | 4.26$^{+1.39}_{-0.99}$ |
| 8541   | 2007 Mar 17 13:02 | 2007 Mar 17 14:54 | 4701 | 2.67$^{+0.96}_{-0.66}$ | 2.90$^{+0.94}_{-0.72}$ |
| 7568   | 2007 May 16 09:30 | 2007 May 16 20:56 | 40268 | 0.69$^{+0.35}_{-0.26}$ | 0.75$^{+0.38}_{-0.28}$ |
| 7569   | 2007 Jun 30 06:19 | 2007 Jun 30 23:48 | 60400 | 2.07$^{+0.74}_{-0.45}$ | 2.25$^{+0.78}_{-0.49}$ |
| 9086   | 2007 Dec 26 01:02 | 2007 Dec 26 09:04 | 27395 | 0.26$^{+0.18}_{-0.12}$ | 0.28$^{+0.19}_{-0.13}$ |
| 9801   | 2007 Dec 28 19:23 | 2007 Dec 28 23:59 | 15068 | 3.34 $\times 10^{-1}$ |
| 9802   | 2007 Dec 29 18:57 | 2007 Dec 30 01:13 | 20239 | 0.28 $\times 10^{-1}$ |
| 9803   | 2008 Jan 5 01:04 | 2008 Jan 5 04:23 | 9986 | 3.34 $\times 10^{-1}$ |
| 9811   | 2008 Apr 30 23:09 | 2008 May 1 08:34 | 32330 | 0.28 $\times 10^{-1}$ |
| 9812   | 2008 May 1 22:45 | 2008 May 2 07:50 | 30775 | 0.28 $\times 10^{-1}$ |
| 9813   | 2008 May 3 15:51 | 2008 May 3 23:35 | 26382 | 0.28 $\times 10^{-1}$ |
| 9814   | 2008 May 4 15:07 | 2008 May 4 23:22 | 27810 | 0.28 $\times 0.13$ |

Notes.

$^a$ Start and End times are given in UT.

$^b$ Observing time given in s.

$^c$ Count rate in units of $10^{-4}$ ACIS-S counts s$^{-1}$ in the 0.5–8.0 keV band.

$^d$ Unabsorbed 0.3–10.0 keV flux in units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$. The count rates were converted assuming $N_H = 1.34 \times 10^{21}$ cm$^{-2}$ and $\beta_X = 0.89$. 

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8 The hardness ratio is defined as $HR = (H - S)/(H + S)$, where $S$ and $H$ are the observed counts in the 0.3–2.0 and 2.0–10.0 keV energy bands, respectively.
Table 2

Fits to the Late-time (T > 10^5 s) Swift XRT and Chandra Light Curve of GRB 060729

| Model          | α₁     | T-break, s⁻¹ | α₄     | T-break, s⁻¹ | α₅     | χ²/ν |  
|----------------|--------|--------------|--------|--------------|--------|------|
| (1) powl fixed  | 1.32   |  ...         |  ...   |  ...         |  ...   | 897/46 |
| (2) powl free   | 1.45 ± 0.01 |  ...         |  ...   |  ...         |  ...   | 400/45 |
| (3) bknpowl     | 1.32 ± 0.03 | 2.08 ± 0.20  | 1.85 ± 0.10 |  ...   |  ...   | 168/43 |
| (4) powl²      | 1.46 ± 0.04 |  ...         |  ...   |  ...         |  ...   | 160/41 |
| (5) bknpowl³   | 1.32 ± 0.02 | 1.23 ± 0.25  | 1.70 ± 0.07 |  ...   |  ...   | 65/39  |
| (6) bknpowl T < 30 Ms⁴ | 1.32 ± 0.05 | 1.01 ± 0.35  | 1.61 ± 0.08 |  ...   |  ...   | 60/37  |
| (7) powl T ≥ 1.2 Ms⁵ |  ...     | 1.61 ± 0.07  |  ...   |  ...         |  ...   | 12/15  |
| (8) powl T ≥ 1.2 Ms, e < 35 Ms⁶ |  ...     | 1.61 ± 0.15  |  ...   |  ...         |  ...   | 6/13   |
| (9) bknpowl T ≥ 1.2 Ms, e |  ...     | 1.61 (fixed) | 41.3 ± 2.0 | 4.65 ± 0.05 | 6/14   |

Notes.

- Break times T-break are given in units of Ms.
- Decay slope fixed to the value given in Grupe et al. (2007).
- Decay slope parameter left free to vary.
- Excluding the two flares at 2 and 5 Ms.
- Error bars of α₄ and T-break are determined by keeping α₄ fixed at the best-fit value for model 4 and assuming that χ² - χ²_{min} follows the Gaussian distribution (see Figure 2).

The late-time light curve (Figure 1) was fitted by several power law and multiple-broken power-law models as listed in Table 2. Fitting the light curve with the decay slope α₃ fixed to 1.32, as reported by Grupe et al. (2007) from the Swift data, gives a very poor result (χ²/ν = 897/46). The fit can be improved by leaving the decay slope as a free parameter (Table 2, model 2). This results in a single decay slope of α₃ = 1.45 ± 0.01, but the light curve still deviates significantly at later times from this slope, resulting in an unacceptable χ²/ν = 400/45. A broken power-law fit to the entire late-time light curve (model 3) reveals a break at about 2 Ms after the burst; in contrast to the result of Grupe et al. (2007), in which we could fit the late-time Swift data with just one decay slope, the addition of the 2007 Chandra data requires a break in the Swift data. The late decay slope, α₄ = 1.85, is driven by the last two Chandra observations, while the χ² is also strongly affected by two very high data points at ~2 Ms and ~5 Ms. Making the assumption that these two high points are late-time X-ray flares unrelated to the afterglow of the external shock, we removed them from further fits (see models 4 and 5). We then fit the data between 100 ks and 30 Ms with a broken power law (model 6), obtaining a break time of T-break,3 = 1.01 ± 0.32 Ms and slopes of α₃ = 1.35 ± 0.02 and α₄ = 1.61 ± 0.06. This fit is plotted as the dashed line in Figure 1.

The last two Chandra observations deviate from this fit, suggesting a break at about a year after the burst. Because these last two points have very few counts (and consequently large uncertainties), a broken power-law fit to the late-time light curve cannot constrain either the break time or the late-time decay slope α₄ unless at least one parameter is fixed. We therefore approached the question of a final break in steps. A single power-law fit to the light curve for T ≥ 1.2 Ms (Table 2, model 7) gives α₄ = 1.68 ± 0.08 and χ²/ν = 12/15. Although this is already an acceptable fit, we investigated the possibility of a late-time break which is expected from GRB theory (compare, e.g., Zhang et al. 2006; Mészáros 2006). At first we fitted the light curve for 1.2 Ms ≤ T ≤ 35 Ms with a single power law (model 8) which results in α₄ = 1.61 ± 0.07 and χ²/ν = 6/13. We then fitted a broken power-law model to the entire light curve with T > 1.2 Ms with α₄ fixed at 1.61 (the best-fit result when the last two Chandra observations are excluded; model 8 in Table 2) to determine whether the data require a very late break in the light curve slope. This fit (Table 2, model 9) gives T-break,4 = 41.3 ± 2.0 Ms and α₄ = 4.65 ± 0.05, with χ²/ν = 6/14. Figure 2 displays the contour plot between the final break time and the final slope. It shows that they are still not well constrained. Although the best-fit break time is 41 Ms (2007 November), a break as early as ~26 Ms, with a late-time decay slope of α₄ = 2.5, is consistent with the data at the 1 σ level.

In addition to the broken power-law fits with a sharp break, the late-time light curve was also fitted by the smoothed double-broken power-law model defined by Beuermann et al. (1999). Here, we found the decay slopes α₃ = 1.20 ± 0.07, α₄ = 1.70 ± 0.05, and α₅ = 2.41 ± 0.26 with break times at 1.09 ± 0.01 and 20 Ms (fixed). The smooth parameter is fixed to 3.0 and 2.0 for the breaks at about 1 and 20 Ms, respectively. This results in an acceptable fit with χ²/ν = 42/32. Possible interpretations of these temporal breaks are discussed in Section 4.
3.2. Spectral Variations

Temporal breaks are often associated with spectral breaks (e.g., Sari et al. 1998; Mészáros et al. 1998; Zhang et al. 2006). Figure 3 displays the Swift XRT count rate and hardness ratio light curves for the interval between 100 ks and 5 Ms after the burst. The hardness ratios are plotted segment by segment. While the hardness ratios before the break at 1 Ms after the burst are of order \( HR \sim 0.3 \), after the break the spectrum hardens to \( HR \sim 0.45 \) with even harder values at later times.

The spectrum before the 1 Ms break can be fitted with a single absorbed power law with \( N_{HI} = (1.34^{+0.27}_{-0.20}) \times 10^{21} \text{ cm}^{-2} \) and an energy spectral slope \( \beta_x = 1.18 \pm 0.11 (\chi^2/\nu = 81/82) \). The spectrum after the 1 Ms break was also fitted by an absorbed single power-law model. Leaving the absorption column density as a free parameter, however, results in an increase of the column density, which does not seem plausible. Therefore, we fixed the absorption column density to \( N_{HI} = 1.34 \times 10^{21} \text{ cm}^{-2} \), the value obtained before the break. This fit results in a slightly flatter energy spectral slope \( \beta_x = 0.89 \pm 0.11 \). These values were used in PIMMS to convert the Chandra ACIS-S count rates into the fluxes given in Table 1 and plotted in Figure 1.

The Chandra data must be analyzed in the Poisson limit, complicating proper analysis of possible spectral variations at very late times. Using the Bayesian approach described by Park et al. (2006), we estimated the hardness ratios in the Chandra data and their uncertainties, both before and after the break at 38 Ms. We obtain mean values of \( HR = -0.39 \) for the 2007 March–June data (before the final break; 38 counts total) and \( HR = -0.80 \) for the very late data (after the final break; eight counts total), with 85% confidence limits of \( HR = -0.60 \) to \(-0.17 \) and \( HR = -1.00 \) to \(-0.58 \), respectively. Although this is a suggestion of spectral softening across the final break, we cannot exclude (at the 85% confidence level) the possibility that the hardness ratio is constant. Note that due to the different energy bands and detector response matrices it is not possible to compare the Swift and Chandra hardness ratios directly.

3.3. Comparison with Other GRBs

Even though GRB 060729 was one of the brightest bursts detected in X-rays, it is not the brightest one so far seen during the Swift mission. GRB 061121 was about 2–3 times brighter when the Swift XRT started observing it (Page et al. 2007), but by a day after the burst it was an order of magnitude fainter than GRB 060729 and was not detected after 2 Ms post-burst. The second brightest X-ray afterglow so far seen by Swift was GRB 080319B (Racusin et al., 2008). Figure 4 displays the observed count rate light curves of GRBs 060729, 061121, and 080319B. Even though GRBs 061121 and 080319B appear to be much brighter than GRB 060729 until about 20 ks after the trigger, the long plateau phase in GRB 060729 makes it the brightest X-ray afterglow about half a day after the trigger. GRB 061121 already displays a break from the plateau to the second steep decay phase at 2.2 ks after the burst followed by an even steeper decay at 30 ks with a decay slope of \( \alpha = 1.5 \) (Page et al. 2007). This earlier break compared to GRB 060729, which broke at about 60 ks after the burst, and the steeper decay slope of 1.5 compared to 1.3 in GRB 060729 made GRB 061121 disappear much faster than GRB 060729. The “naked-eye” burst 080319B on the other hand does not even show a noticeable plateau phase and decays rather quickly with late-time decay slopes of \( \alpha_X = 1.17 \) and 2.61 before and after the late-time jet break at \( T = 9.5 \times 10^5 \) s.

We can ask how the intrinsic rest-frame 2–10 keV luminosity light curve of GRB 060729 compares to the bursts shown in Figure 1 in Nousek et al. (2006). Figure 5 displays GRBs 060729, 061121, and 080319B with most of the bursts shown in Figure 1 in Nousek et al. (2006) in the rest frame. The plot shows that during the plateau phase, GRB 060729 was not that luminous. As a matter of fact, it was a factor of about 10–100 less luminous than bursts such as GRBs 061121 or 080319B.

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10 We defined the Chandra hardness ratio as \( HR = (H - S)/(H + S) \), where \( S \) and \( H \) are the counts in the 0.5–2.0 and 2.0–8.0 keV bands, respectively.
Nevertheless, after a few days in the rest frame, GRB 060729 becomes the most luminous X-ray afterglow in the 2–10 keV band.

Compared with other GRBs shown in Figure 5, the total energy output in the apparent rest-frame 2–10 keV band of $E_{2–10\text{ keV}} = 7 \times 10^{52}$ ergs makes GRB 060729 one of the most energetic X-ray afterglows ever detected. In the 2–10 keV band, only GRBs 061121 and 080319B appear to be more energetic with $E_{2–10\text{ keV}} = 1 \times 10^{53}$ ergs and $2 \times 10^{54}$ ergs, respectively. However, if we attempt to correct for the jet opening angle, the picture changes. With jet opening angles of 4° and 0.4° as inferred for GRBs 061121 and 080319B, respectively (Page et al. 2007; Racusin et al. 2008), the beaming-corrected energies are $2.4 \times 10^{50}$ and $4.0 \times 10^{50}$ ergs, respectively. For GRB 060729, however, assuming a jet half-opening angle of 14° (see next section), the beaming-corrected energy is still $2.1 \times 10^{51}$ ergs in the rest-frame 2–10 keV band.

4. DISCUSSION

While our original Swift X.RT light curve after the plateau phase seems to be consistent with a single power-law decay (Grupe et al. 2007), the Chandra data make it apparent that there had to be a break at about 1 Ms after the burst. We showed above that this break coincided with a significant change in the X-ray spectral slope from $\beta_X = 1.2$ before and 0.9 after that break. Unfortunately, as mentioned in Grupe et al. (2007), Swift could only follow the afterglow in the UVOT with the W1 filter up to a month after the burst due to bright stars in the UVOT field which caused some scatter in the UVOT and an enhanced background at the position of GRB 060729.

According to model 9 (excluding the two X-ray flare points at 2 Ms and 5 Ms) in Table 2, the late-time X-ray afterglow is described by $F_{\nu_X} \propto t^{-\alpha_3} \nu_X^{-\beta_X}$, where (1) $\alpha_3 = 1.32^{+0.02}_{-0.03}$, $\beta_3 = 1.18 \pm 0.11$ for $105 \text{ ks} < t < T_{\text{break,3}} = 1.01^{+0.35}_{-0.22} \text{ Ms}$; (2)
\( \alpha_4 = 1.61^{+0.10}_{-0.09}, \beta_4 = 0.89 \pm 0.11 \) for \( T_{\text{break},3} < t < T_{\text{break},4} = 4.13^{+0.51}_{-0.53} \times 10^3 \) s; and (3) \( \alpha_5 = 4.65^{+0.05}_{-0.03} \) for \( t > T_{\text{break},4} \).

The closure relation for 0.1 Ms < \( t < 1.0 \) Ms results in \( \alpha_2 - 1.5\beta_2 = 0.46 \pm 0.17 \), consistent with both the interstellar medium (ISM) and wind models with theoretical expectation of \( \alpha_2 - 1.5\beta_2 = -0.5 \) if \( v_X > \max\{v_c, v_{\text{env}}\} \), so \( \alpha_2 = (3\beta - 2)/4 \) and \( \beta_2 = \beta/2 \). The power-law index of the electron energy distribution is \( p = 2.43^{+0.03}_{-0.07} \) (2.36 ± 0.22), derived from \( \alpha_3(\beta_3) \). The closure relation for 1.0 Ms < \( t < 41 \) Ms results in \( \alpha_2 - 1.5\beta_2 = 0.28^{+0.13}_{-0.08} \), moderately consistent with the theoretical expectation of \( \alpha_2 - 1.5\beta_2 = 0.5 \) if the environment is a free wind and the spectral regime is \( v_m < v_X < v_c \), so \( \alpha_4 = (3\beta - 1)/4 \) and \( \beta_4 = (p - 1)/2 \). In other words, the break at \( t \sim 1.0 \) Ms can be interpreted as a cooling break in the wind medium scenario in which the cooling frequency \( v_c \) crosses the X-ray band. The power-law index of the electron energy distribution derived from the value of \( \alpha_2 \) (the spectral index of this epoch has a relatively large uncertainty) is \( p = 2.48^{+0.13}_{-0.08} \), quite consistent with the value derived during the previous epoch. Therefore, a wind model is preferred from the observations before \( t = 41 \) Ms, breaking the degeneracy of the wind and ISM models both of which are consistent with the earlier data (Grupe et al. 2007).

The X-ray afterglow light curve for \( t > 2.75 \times 10^3 \) s excluding the two flares can be also well fitted by a single smoothed broken power law: (1) \( \alpha_2 = 1.31 \pm 0.05 \), \( \beta_2 = 1.18 \pm 0.11 \) for 275 ks < \( t < T_{\text{break},3} = 2.43 \pm 0.79 \) Ms and (2) \( \alpha_2 = 1.96 \pm 0.09 \), \( \beta_2 = 0.89 \pm 0.11 \) for \( T_{\text{break},3} < t < (x_4^2/dof) = 42/32, \) smoothness parameter \( s = 3 \). The steepening of the decay at \( t > 2.4 \) Ms, if not due to the cooling frequency passing through the observing band (which results \( \alpha_2 - \alpha_3 = 0.25 \), inconsistent with the observation), should originate from the post-jet-break evolution. The change of the temporal decay index, \( \alpha_2 - \alpha_3 = 0.65 \pm 0.10 \), is consistent with a non-spatial jet break in a wind model with \( \Delta \alpha = 0.5 \) (if the jet has significant sideways expansion, then the value of \( \alpha_2 \) should be equal to \( p = 2.4 \pm 2.5 \)). However, the spectral hardening around the break time cannot be well interpreted in such a model. Furthermore, the transition of a jet break in the wind medium usually takes 2 orders of magnitude in time (Kumar & Panaitescu 2000), which is inconsistent with the observation of GRB 060729. In conclusion, the temporal break at \( t \sim 1-3 \) Ms is probably not a jet break.

There are two possible interpretations for the last tentative light curve break at \( t = 41 \) Ms: a jet break and a spectral break in a spherical model. We discuss these next, after which we consider the implications of the long plateau phase.

### 4.1. Jet Model

The jet + wind model predicts \( \alpha_5 = p \sim 2.4-2.5 \) for a sideways expanding jet or \( \alpha_5 = \alpha_4 + 0.5 \sim 2.1 \) for a non-sideways expanding jet. The value of the model-predicted temporal index after the jet break thus cannot be excluded at even the 1σ confidence level (see Figure 2). Recently, Zhang & MacFadyen (2009) have performed two-dimensional simulations and calculations of GRB afterglow hydrodynamics and emission. They showed that the sideways expansion of GRB jets can be neglected during the relativistic phase (for the sideways expansion of GRB jets see also Kumar & Granot 2003; Granot & Kumar 2003) and that the change in the decay slope was larger than predicted analytically. Their results may further alleviate the above problem of the relatively shallow theoretical slope compared with the observed steep slope. However, the spectral softening revealed by the hardness ratio evolution around this break time somewhat disfavors the jet break interpretation.

If we interpret this break as a jet break, then a half-opening angle of the jet can be inferred (e.g., Chevalier & Li 2000). Under the thin-shell approximation for the post-shocked fluid of a relativistic blast wave, the conservation of energy (neglecting the initial baryon loading in the fireball) reads

\[ E_{k,\text{iso}} = M_{sw} \Gamma^2 c^2 = \text{constant}, \]

where \( \Gamma \) is the bulk Lorentz factor of the downstream fluid just behind the shock front and \( \Gamma \) = \( \sqrt{2 \Gamma} \) is the Lorentz factor of the shock. The swept-up circum-burst mass by the blast wave is

\[ M_{sw} = \int_0^R 4\pi r^2 n(r) m_p dr = 4\pi \frac{4}{3 - k} AR^{3-k} m_p, \]

where the environmental density \( n(r) = Ar^{-k} \), and \( A = n_0 \) for the ISM case (\( k = 0 \)) and \( A = 3 \times 10^{35} \) cm\(^{-1} \) \( A_s \) for the stellar wind case (\( k = 2 \)).

The evolution of the shock radius \( R \) measured in the observer’s frame is \( dR = 2\Gamma^2 cdt/(1+z) \); therefore,

\[ R = \left[ \frac{(3-k)(4-k)}{(1+z)^2 \pi A m_p c^2} \right]^{1/(4-k)}, \]

and

\[ \Gamma = \left[ \frac{(3-k)E_{k,\text{iso}}}{4\pi A R^{3-k} m_p c^2} \right]^{1/2}. \]

Inserting the inferred values of the physical parameters, we have

\[ R = 1.2 \times 10^{19} E_{k,\text{iso},54} n_0^{-1/4} \left( \frac{t}{41 \text{ Ms}} \right)^{1/4} \text{ cm}, \]

\[ \Gamma = 1.0 E_{k,\text{iso},54} n_0^{-1/4} \left( \frac{t}{41 \text{ Ms}} \right)^{-3/8}, \]

for the ISM case, and

\[ R = 1.0 \times 10^{20} E_{k,\text{iso},54} A_{s,-1}^{-1/4} \left( \frac{t}{41 \text{ Ms}} \right)^{1/2} \text{ cm}, \]

\[ \Gamma = 4.0 E_{k,\text{iso},54} A_{s,-1}^{-1/4} \left( \frac{t}{41 \text{ Ms}} \right)^{-1/4}, \]

\[ \theta_{\text{jet}} = 14\pi E_{k,\text{iso},54} A_{s,-1}^{1/4} \left( \frac{t}{41 \text{ Ms}} \right)^{1/4}, \]

for the wind case. The values of \( E_{k,\text{iso}} \) and \( A_s \) adopted here can be found below. We adopt the convention of \( Q_x = Q/10^x \) in cgs units. Unless \( n_0 \ll 0.1 \) cm\(^{-3} \), the jet has already decelerated to be non-relativistic (\( \Gamma \sim 2 \)), while the fact that there was no jet break before \( t = 4.1 \times 10^3 \) s argues against the jet in an ISM medium. In other words, the outflow of GRB 060729 is likely spherical if the circum-burst medium is ISM. However, in this...
way the temporal break at $T_{\text{break,4}}$ cannot be explained with the hydrodynamic/geometry effect.

At such a late time, the jet may also enter the non-relativistic phase in a stellar wind medium and the hydrodynamics is described by the self-similar Sedov–von Neumann–Taylor solution. The non-relativistic transition time\(^{12}\) is (Waxman 2004)

$$I_{\text{SNT}} = 2.7 E_{\text{jet,52}} A_{\ast,1}^{-1} \text{ yr},$$

where $E_{\text{jet}} \approx E_{\text{k,iso}}\theta_{\text{jet}}^2/4$ is the beaming-corrected kinetic energy of the outflow. The non-relativistic transition predicts a flattening in the light curve (Huang & Cheng 2003; Zhang & MacFadyen 2009). The theoretical temporal slope is $\alpha = (7p - 5)/6 \approx 2.0 - 2.1$ for $p \sim 2.4 - 2.5$, which is not inconsistent with the observations if the large error bars of the observed slope are considered. However, the trend of steepening after the break contradicts the trend of flattening when the jet becomes non-relativistic.

The jet is still inside the free wind bubble $\sim 450$ days after the burst in the observer’s frame, indicating that the termination shock radius of the wind bubble is larger than $\sim 32$ pc. The size of a GRB progenitor star wind bubble depends on the density and pressure of external ISM and the mass loss history of the star-burst environment. Further deep optical observation of GRB 060729 is not likely to be located in a giant molecular cloud and (3) the density and pressure of the external ISM should be low. Therefore, from modeling the afterglow, the progenitor of GRB 060729 is not likely to be located in a giant molecular cloud or a star-burst environment. Further deep optical observation of the GRB site and its host galaxy may help to test this prediction.

4.2. Spherical Model

We assume that the initial shock-accelerated electrons at such a late time have a broken power-law distribution,

$$\frac{dN_e}{d\gamma_e} = N_p \times \begin{cases} \gamma_e^{-p_1}, & \gamma_m < \gamma_e < \gamma_b, \\ \gamma_b^{-p_2}, & \gamma_b < \gamma_e, \end{cases}$$

where $p_1 = p \sim 2.4$ is the low energy power-law index and $p_2$ is the high energy power-law index, $\gamma_b$ is the break Lorentz factor of electrons. This assumption is much more realistic than the single power-law assumption, especially for the late time when the shock Lorentz factor decreases to the order of unity/ the shock is no longer ultra-relativistic (e.g., Hededal et al. 2004; Niemiec & Ostrowski 2006; Spitkovsky 2008). For simplicity, we assume $R_b = \gamma_b/\gamma_m$ remains a constant in time (Li & Chevalier 2001). In this scenario, $\tau_c (\tau_c = \gamma_c / \gamma_b) = 1.3 \times 10^6 s$ and $\tau_p (\tau_p = \gamma_p / \gamma_b, \gamma_p$ is the typical synchrotron frequency of $\gamma_b$ electrons) is equal to $4.1 \times 10^7 s$. The last steep decay segment can be described with $\alpha_s = (3p_2 - 1)/4$ and $\beta_s = (p_2 - 1)/2$. The high energy power index is therefore derived to be $p_2 = 6.5 \pm 0.37, -1.79$, and the inferred spectral index is $\beta_s = 2.77 \pm 0.37, 0.99$. From $t_m \ll 10^5 s$ and $t_p = 4.1 \times 10^7 s$, we constrain the parameter $R_b \gtrsim (4.1 \times 10^7/10^3)^{3/4} \sim 91$. The above $p_1 \sim 2.4, p_2 \sim 6.5, R_b \gtrsim 91$ are quite similar to those derived from GRBs 991208 and 000301C in Li & Chevalier (2001).

The synchrotron emission from a spherical relativistic blast wave can be described by (e.g., Chevalier & Li 2000; Wu et al. 2005)

$$v_m = 3.7 \times 10^{12} \epsilon_e^{-0.5} \epsilon_B^{-1/2} E_{\text{k,iso},53}^{1/2} A_{\ast,5}^{-3/2} \text{ Hz},$$

$$v_c = 3.4 \times 10^{13} \epsilon_e^{-1} \epsilon_B^{-1/2} E_{\text{k,iso},53}^{1/2} A_{\ast,5}^{2/3} \text{ Hz},$$

$$F_{\nu, \text{max}} = 111 \epsilon_e^{-1/2} \epsilon_B^{-1/2} E_{\text{k,iso},53}^{1/2} A_{\ast,5}^{-1/2} \text{ mJy},$$

where $\epsilon_e, \epsilon_B$ are the energy equipartition fractions of electrons and magnetic field, respectively, $A_\ast$ is the stellar wind parameter. We have considered the cooling effect on $v_c$ by synchrotron self-Compton scattering processes. The crossing time $t_m$ in the optical band ($v_{\text{opt}} \sim 10^{15} \text{ Hz}$) by $v_m$ no more than $t = 10^5 s$ gives

$$\epsilon_e^{-0.5} \epsilon_B^{-1/2} E_{\text{k,iso},53} \lesssim 7.3 \times 10^4,$$

which is easily satisfied, while the crossing time $\tau_c$ in the X-ray band ($h \nu_x \sim 2 \text{ keV}$) by $v_c$ gives

$$\epsilon_e^{-1/2} \epsilon_B^{-1} E_{\text{k,iso},53}^{1/2} A_{\ast,5}^{-1/2} \sim 2.24 \times 10^{-4}.$$
et al. (2007). Adopting a typical GRB efficiency of 10%–90%,
the initial isotropic kinetic energy remaining in the afterglow
shock is about the same order of $E_{k,iso}$, i.e., $E_{k,iso} \sim 10^{52}$ ergs.
After the energy injection is finished, the shock energy $E_{k,iso}$ is
increased by a factor of ~100 compared to its initial value, so
$E_{k,iso}$ is the order of $\sim 10^{54}$ ergs. The lack of a jet break up to
$t = 642$ days results in a lower limit of the half-opening angle of
the GRB jet, i.e.,

$$\theta_j \gtrsim 15^\circ E_{k,iso,54}^{-1/4} A_{\nu,1}^{1/4},$$

(18)

which corresponds to a beaming-corrected jet (double-sided)
energy of

$$E_{jet} \gtrsim 3.4 \times 10^{52} E_{k,iso,54}^{-1/2} A_{\nu,1}^{-1/2} \text{ergs}.$$  (19)

This makes it one of the most energetic jets ever seen and is
the reason why we were still able to detect the X-ray afterglow
642 days after the burst. Note that the energy of a fastest-rotating
magnetar is $E_M = \frac{1}{2} I \Omega^2 \lesssim 2 \times 10^{52} I_4 S_2 P_{ms}^{-2}$ ergs. A massive
and fast-rotating black hole as the central engine is thus more
likely to provide the required energy.

5. CONCLUSION

What makes the X-ray afterglow of GRB 060729 so remark-
able is the fact that it was still detected even almost two years
after the burst. This exceptional late-time detectability is related
to three things: (1) with an initial 0.3–10.0 keV flux of almost
$10^{-7}$ erg s$^{-1}$ cm$^{-2}$ it was one of the brightest afterglows ever
detected by Swift, (2) its flat decay phase (Nousek et al. 2006;
Zhang et al. 2006) extended out to about 60 ks after the burst,
and (3) the decay slope after that break is about $\alpha = 1.3$. Despite
breaks at $T \sim 1$ Ms and $T \sim 1$ year, the afterglow was still
detected by Chandra nearly two years after the burst. Bursts
like GRB8 060614, 061121, or even 080319B (Mangano et al.
2007; Page et al. 2007; Racusin et al. 2008, respectively) were
like GRBs 060729, but their plateau phases are significantly shorter than
at 61 around this break and the X-ray
spectrum hardened in the meantime, indicating this break is a
cooling break (the cooling frequency of synchrotron radiation
crosses the X-ray band). There is another light curve break
at $\sim 1.3$ year after the burst tentatively indicated by the last
two Chandra detections. This break coincides with a possible
spectral softening, suggesting that the break may be of spectral
origin, though a hydrodynamic origin (jet break) is also possible.
If due to a jet break, then the implied half-opening angle is
$\theta_j \sim 14^\circ$. If due to a spectral break, such a spectral softening
could be the result of a very steep power-law distribution of
shock-accelerated electrons responsible for the synchrotron
radiation. In this case, with no evidence for a jet break up to 642
days after the burst by Chandra, the jet half-opening angle must
be $\theta_j > 15^\circ$ and the jet energy $E_j > 3 \times 10^{52}$ erg. Such a large
jet energy implies that the central engine must be a fast-rotating
massive black hole, not a magnetar.

Our Chandra observations presented here have shown again
how important Chandra is for late-time observations of GRB X-ray
afterglows. Chandra has already been essential for the detection
and non-detection of jet breaks in the X-ray afterglows of
the short-duration GRBs 050724 and 051221A (Grupe et al.
2006; Burrows et al. 2006, respectively).

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