

## GRB 060714: NO CLEAR DIVIDING LINE BETWEEN PROMPT EMISSION AND X-RAY FLARES

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### ABSTRACT

The long gamma-ray burst GRB 060714 was observed to exhibit a series of five X-ray flares beginning  $\sim 70$  s after the burst trigger  $T_0$  and continuing until  $\sim T_0 + 200$  s. The first two flares were detected by the Burst Alert Telescope (BAT) on the *Swift* satellite, before *Swift* had slewed to the burst location, while the last three flares were strongly detected by the X-Ray Telescope (XRT) but only weakly detected by the BAT. This burst provides an unusual opportunity to track a complete sequence of flares over a wide energy range. The flares were very similar in their light curve morphology, showing power-law rise and fall components, and in most cases significant substructure. The flares also showed strong evolution with time, both spectrally and temporally. The small timescale and large amplitude variability observed are incompatible with an external shock origin for the flares, and support instead late-time sporadic activity either of the central source or of localized dissipation events within the outflow. We show that the flares in GRB 060714 cannot be the result of internal shocks in which the contrast in the Lorentz factor of the colliding shells is very small, and that this mechanism faces serious difficulties in most *Swift* GRBs. The morphological similarity of the flares and the prompt emission and the gradual and continual evolution of the flares with time makes it difficult and arbitrary to draw a dividing line between the prompt emission and the flares.

*Subject headings:* gamma rays: bursts

### 1. INTRODUCTION

One of the most surprising findings of the studies of gamma-ray bursts (GRBs) made with the *Swift Gamma-Ray Burst Explorer* (Gehrels et al. 2004) is that nearly half of all bursts show flares, or large short-lived increases in emission at times after the initial prompt emission has died away (Burrows et al. 2005b; Nousek et al. 2006; O’Brien et al. 2006). These flares are superimposed on either the rapidly decaying tail of the prompt emission, or the very slowly decaying phase of the early afterglow, and can involve flux increases of as much as 3 orders of magnitude. Some bursts have single flares, although most bursts with flares have multiple flaring episodes. Most flares are at early times,  $t \lesssim 10^3$  s, although strong flares can occur as late as  $\gtrsim 10^4$  s after the onset of the burst.

The origin of GRB flares is still an open question. Evidence is mounting, however, that the origin of these flares is similar to that of the prompt GRB emission (i.e., either internal shocks or some other well-localized dissipation process within the ultrarelativistic outflow), rather than to that of the afterglow emission (i.e., the external shock going into the ambient medium). This evidence includes the multiplicity of flares; their sharp time structure (rapid rise and decay and subpeak structure within the flares); the large increase in flux during the flare; and the hard to soft spectral evolution of the flares, which is similar to the spectral evolution found in the prompt emission.

In the context of the internal shocks model (Rees & Mészáros 1994), flares may be caused by late-time collisions of shells of relativistic material that are produced by the central engine with varying Lorentz factors. These can occur either by late-time spo-

radic activity of the central source, or by a small relative velocity between shells that were ejected during the prompt GRB emission (e.g., Burrows et al. 2007).

Very few GRBs have a sequence of multiple flares bright enough to be studied in detail. GRB 060714 (Krimm et al. 2006a) showed a series of five flares starting at  $\sim 70$  s after the start of the burst. The first three flares were clearly detected by the *Swift* Burst Alert Telescope (BAT; Barthelmy et al. 2005a), and the last three were seen as strong flares by the *Swift* X-Ray Telescope (XRT; Hill et al. 2004; Burrows et al. 2005a) and as weak flares by the BAT. The first two flares occurred while the spacecraft was slewing to or settling at the burst location, so they were not observable by the XRT. This burst provides a rare opportunity to study a rapid sequence of flares across a large energy range. The five flares show evidence of hard to soft spectral evolution as the flares progress and also strong similarities, in particular, sharply resolved temporal features and large flux increases in each flare. We show that these results are inconsistent with an external shock (i.e., afterglow) origin for the flares and suggest instead a late-time and lower energy continuation of the prompt emission, either due to late-time intermittent activity of the central source or via well-localized spasmodic dissipation events within the outflow.

In fact these results suggest that it may no longer be possible to draw a clear distinction between what have traditionally been called the prompt emission and the X-ray flares. Historically, the prompt emission was that detected above  $\sim 20$  keV and was generally considered to be due to activity of the central engine. X-ray flares are usually detected most strongly at lower energies, so they were considered a completely separate phenomenon. Since we show here that (1) the flares of GRB 060714 are very likely of common origin to the earliest emission from the burst, (2) the flares are detected above 20 keV, and (3) the flares show a gradual and continual evolution linking them to the prompt emission, it is quite reasonable to consider the flares a lower energy continuation of the same phenomenon as the prompt emission. However, to be consistent with earlier work we do use the term “prompt emission” to refer to the emission in the first peak,  $\sim -13$  s before to 20 s after

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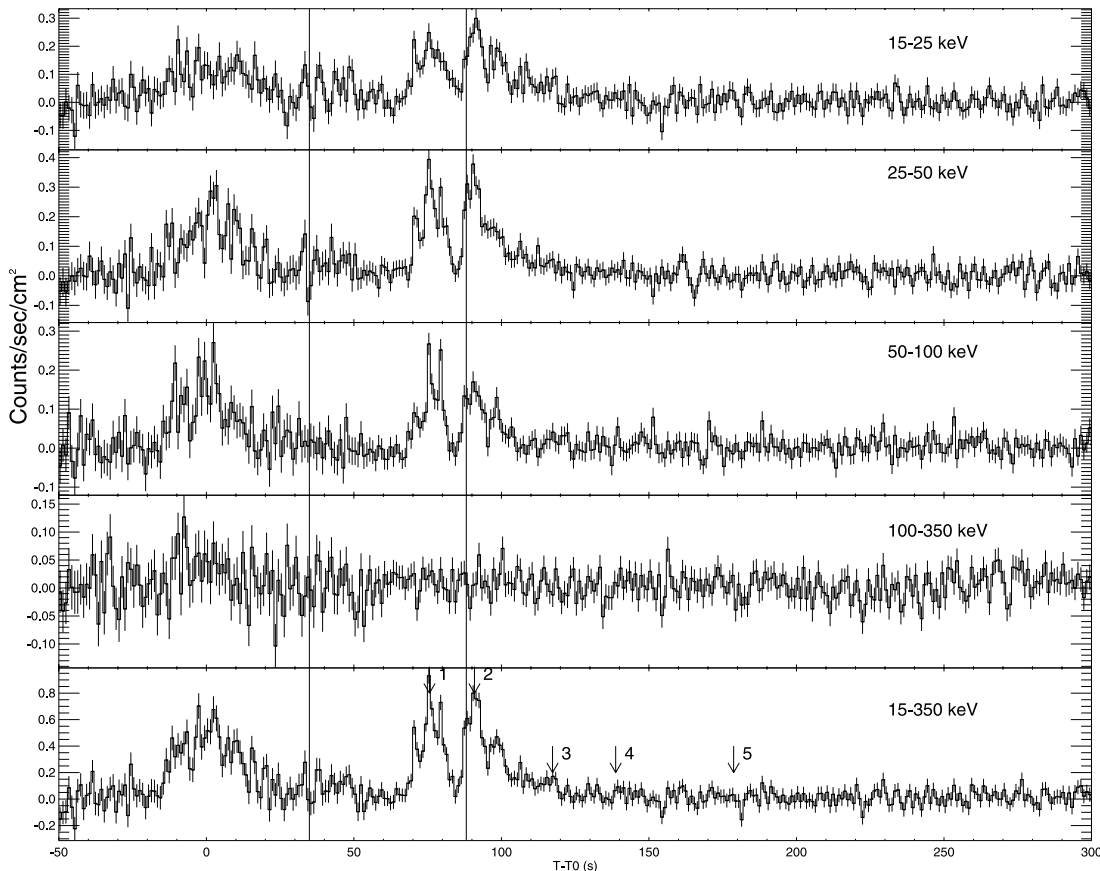


FIG. 1.—BAT light curve in four energy bands and the sum of all energy bands. The vertical bars indicate the start and end of the spacecraft slew to the burst location. Note that the count rate statistical errors are much larger before the slew than after the slew. This is because the burst was detected near the edge of the BAT field of view where only 27% of the detectors were illuminated. None of the apparent sharp structure in the prompt emission is statistically significant. The arrows in the bottom plot indicate the peak and the numbering of each of the flares.

the burst trigger (see § 2.1), “flare” to refer to the peaks more than  $\sim 70$  s after the trigger, and “afterglow” to refer to the smooth decay  $\gtrsim 300$  s from the trigger.

In this paper we describe the prompt, flaring, and afterglow properties of GRB 060714, with particular emphasis on the flares. In § 2 we discuss the observations and data analysis in general, while § 3 focuses on the analysis of the spectral and temporal properties of the flares. Finally, in § 4 we show that the properties of the flares rule out an external shock (or long-lived reverse shock) origin and provide some (although not unequivocal) support for an origin common to that of the prompt emission. In § 4.3 and in the Appendix we exclude internal shocks with a small contrast in the Lorentz factor as the origin of the flares in GRB 060714 and point out that this mechanism faces serious problems for most *Swift* GRBs.

Throughout the paper we follow the convention  $F_{\nu,t} \propto \nu^{-\beta} t^{-\alpha}$ , where the energy spectral index  $\beta$  is related to the photon index  $\Gamma = \beta + 1$ . We have adopted the standard values of the cosmological parameters:  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.27$ , and  $\Omega_\Lambda = 0.73$ . The phenomenology of the burst is presented in the observer frame unless otherwise stated.

## 2. OBSERVATIONS AND DATA ANALYSIS

### 2.1. *Swift* BAT

At 15:12:00 UT, 2006 July 14, the *Swift* Burst Alert Telescope (BAT) triggered and located on board GRB 060714 (BAT trigger = 219101; Krimm et al. 2006a). Unless otherwise speci-

fied, times  $t$  in this paper are measured from the BAT trigger time, (UT 15:12:00.3), hereafter designated  $T_0$ . The burst was detected in the part of the BAT field of view that was 27% coded, meaning that it was  $33.6^\circ$  off-axis and only 27% of the BAT detectors were illuminated by the source. The spacecraft began to slew to the source location at  $T_0 + 34.9$  s and was settled at the source location at  $T_0 + 88.1$  s.

The BAT data for GRB 060714 between  $T_0 - 240$  s and  $+962$  s were collected in event mode with  $100 \mu\text{s}$  time resolution and  $\sim 6$  keV energy resolution (Krimm et al. 2006b). The data were processed using standard *Swift* BAT analysis tools, and the spectra were fit using XSPEC version 11.3. Each BAT event was mask-tagged using `batmaskwtevt` with the best fit source position. Mask tagging is a technique in which each event is weighted by a factor representing the fractional exposure to the source through the BAT coded aperture. A weight of  $+1$  corresponds to a fully open detector and a weight of  $-1$  to a fully blocked detector. Flux from the background and other sources averages to zero with this method. All of the BAT GRB light curves shown in Figures 1 and 2 (see also Fig. 7, below) have been background subtracted by this method. This method is effective even when the spacecraft is moving, since complete aspect information is available during the maneuver.

The mask weighting is also applied to produce weighted, background-subtracted counts spectra using the tool `batbnev`. Since the response matrix depends on the position of the source in the BAT field of view, separate matrices are derived for before the slew, for after the slew, and for individual segments of the light curve during the slew.

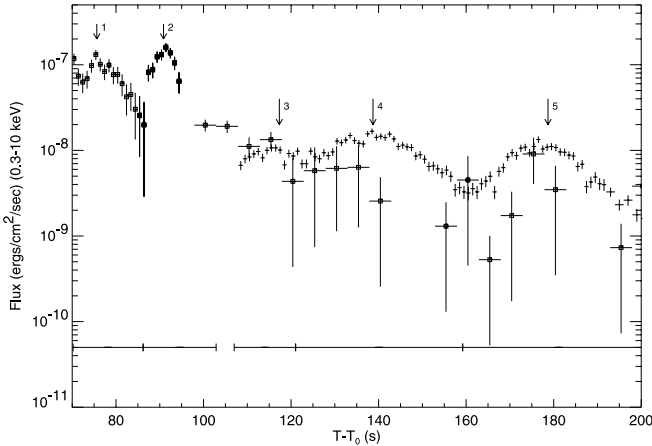


FIG. 2.—Five flares for both BAT (*open squares*) and XRT (*plus signs*). The first XRT flare at  $T \sim 115$  s is clearly detected in the BAT, and there appears to BAT emission at the peak of the flare at  $T \sim 175$  s. The arrows indicate the peak and the numbering of each of the flares. The time for which the spectral fits to the five flares were made are indicated by the bars at the bottom of the plot.

The mask-weighted light curves seen in Figure 1 show an initial triangular-shaped (rising and falling power laws) peak starting at  $T_0 - 15$  s, peaking at  $T_0$ , and ending at  $T_0 + 55$  s. Given the size of the statistical error bars in the time before the slew, none of the fluctuations seen in Figure 1 before the slew are statistically significant. The initial prompt emission was followed by two strong flares, the first starting at  $T_0 + 70.4$  s with a duration of  $\sim 10.5$  s, and the second starting at  $T_0 + 87.6$  s with a duration of  $\sim 12$  s. Finally there was a much weaker third flare, starting at  $T_0 + 108.7$  s with a duration of  $\sim 15.3$  s. Taking into account the prompt emission plus the flares, we derive  $T_{90} = 115 \pm 5$  s (estimated error including systematics).

The time-averaged spectrum from  $T_0 - 13.4$  s to  $+18.0$  s is best fit by a simple power-law model. The power-law photon index of the time-averaged spectrum is  $\Gamma = -d \log N_{\text{ph}} / d \log E_{\text{ph}} = 1.61 \pm 0.13$  ( $\chi^2 = 43.2$  for 59 degrees of freedom). The fluence in the 15–150 keV band is  $(1.22 \pm 0.11) \times 10^{-6}$  erg cm $^{-2}$ . The 1 s peak photon flux measured from  $T_0 + 75.42$  s (during the first flare) in the 15–150 keV band is  $1.4 \pm 0.1$  photons cm $^{-2}$  s $^{-1}$ . The prompt component does show spectral evolution, as evidenced by the increasing power-law index:  $1.47 \pm 0.19$  for  $T_0 - 13.4$  to  $+2.1$  s,  $1.61 \pm 0.17$  for  $T_0 + 2.1$  to  $+18.0$  s, and  $2.29 \pm 0.49$  for  $T_0 + 18.0$  to  $+70.2$  s. All the quoted errors are at the 90% confidence level.

We attempted to fit a model consisting of a power law with an exponential cutoff to the prompt emission. Such a fit did not constrain  $E_{\text{pk}}$ , the peak of the  $\nu F(\nu)$  spectrum. However, it may be possible to use the results of Zhang et al. (2007) to estimate  $E_{\text{pk}}$  for the prompt emission. Zhang et al. (2007) have shown that due to the relatively narrow energy band of BAT, it is often difficult to constrain  $E_{\text{pk}}$ , even when  $E_{\text{pk}}$  is within the BAT energy range. These authors have found that the power-law photon index  $\Gamma$  of a simple power-law fit and  $E_{\text{pk}}$  are well correlated with a relationship

$$\log E_{\text{pk}} = (2.76 \pm 0.07) - (3.61 \pm 0.26) \log \Gamma, \quad (1)$$

under the assumption that  $E_{\text{pk}}$  is within the BAT energy range. Sakamoto et al. (2007) have reached a similar conclusion and consistent result by combining simulations and a study of bursts for which  $E_{\text{pk}}$  has been determined. We can use equation (1) and the measured  $\Gamma = 1.61$ , to find that  $E_{\text{pk}} = 103.1^{+34.0}_{-25.5}$  keV. This

value of  $E_{\text{pk}}$  is consistent with the majority of long GRBs detected by BAT. However, another possibility is that  $E_{\text{pk}}$  is above the BAT energy range ( $> 150$  keV), and 1.61 is instead simply the low-energy power-law index  $\alpha$ . According to the study of Kaneko et al. (2006) a value of  $\alpha = 1.61$  is within the range of  $\alpha$  values found for BATSE bursts, although only 22 of the 350 bursts in the BATSE sample (6.3%) have  $\alpha > 1.61$ . Since we cannot exclude this second possibility, we will be conservative and quote only a lower limit,  $E_{\text{pk}} > 77.6$  keV (taking the lower limit on  $E_{\text{pk}}$  as derived from eq. [1]). As discussed in § 3,  $E_{\text{pk}}$  is well constrained for the later flares.

## 2.2. *Swift* XRT

The spacecraft slewed immediately to the BAT location of GRB 060714 and the *Swift* X-Ray Telescope (XRT) began observing the burst at 15:13:39 UT ( $T_0 + \sim 99$  s), first in Image mode and then in Photodiode (PD) mode. The Image mode contains no spectral or timing information and the PD mode data is severely corrupted by the presence of two hot columns. Thus, the first usable data is in Windowed Timing (WT) mode beginning at  $T_0 + 107$  s (see Hill et al. 2004 for a description of XRT readout modes). Starting from  $T_0 + 249$  s all observations were carried out in Photon Counting (PC) mode.

The XRT data were processed with the XRTDAS software (ver. 1.7.1) developed at the ASI Science Data Center and included in the HEASoft package (ver. 6.0.4). Event files were calibrated and cleaned with standard filtering criteria with the `xrtpipeline` task using the latest calibration files available in the *Swift* CALDB distributed by HEASARC. Event lists were selected in the 0.3–10.0 keV energy band and grades 0–12 for PC mode data and grades 0–2 for WT data were used in the analysis (see Burrows et al. 2005a for a definition of XRT event grades).

The XRT PC image of the field clearly showed a bright fading X-ray object in the field (Perri et al. 2006). The coordinates of the burst were determined by the XRT to be (J2000.0) R.A. =  $15^{\text{h}} 11^{\text{m}} 26.5^{\text{s}}$  ( $227.8604^\circ$ ), decl. =  $-6^\circ 33' 59.3''$  ( $-6.5665^\circ$ ) with a 90% confidence error circle radius of  $3.8''$ .

Events for temporal and spectral analysis of WT mode data were selected using a 40 pixel wide rectangular region centered on the afterglow. Background events were extracted from a nearby source-free rectangular region with a 40 pixel width. Data in PC mode during the first *Swift* orbit (from  $T_0 + 249$  s to  $+1610$  s) were significantly affected by pileup. By comparing the observed point-spread function (PSF) profile with the analytical model (Moretti et al. 2005), we removed pileup effects by excluding events within a 2 pixel radius circle centered on the afterglow position and using an outer radius of 20 pixels. From the second orbit, the afterglow count rate was below the XRT pileup limit and events were extracted using a 10 pixel radius circle. The background for PC mode was estimated from a nearby source-free circular region of radius 50 pixels. Source count rates for temporal analysis were corrected for the fraction of PSF falling outside the event extraction regions and for pixels partially exposed. Ancillary response files for the spectral analysis were generated with the `xrtmkarf` task applying corrections for the PSF losses and pixel exposures. The latest response matrices (ver. 008) available in the *Swift* CALDB were used and source spectra were binned to ensure a minimum of 20 counts per bin.

As discussed in detail in § 3, the XRT light curve (Perri et al. 2006) shown in Figures 2 and 3 (see also Fig. 7, below) displays three flares during the first orbit, peaking at about  $T_0 + 115$ , 140, and 180 s after the BAT trigger. There is a steep decay after the end of the third XRT flare, with temporal power-law index

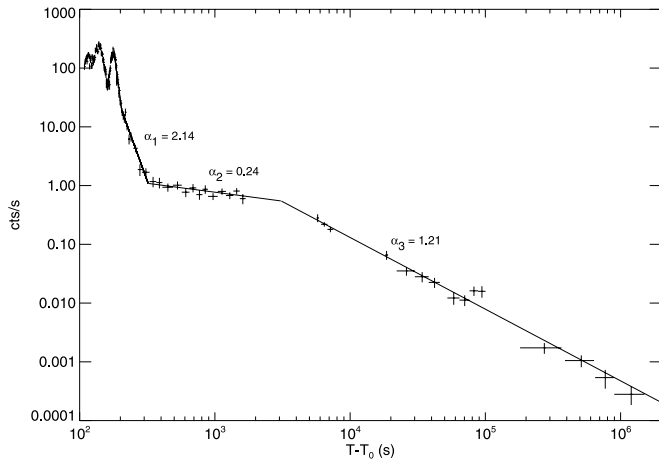


FIG. 3.—XRT light curve showing the early-time flares and three episodes of smoothly decaying afterglow emission.

$\alpha_1 = 2.14 \pm 0.13$ , followed by a much shallower decay starting at  $t_{\text{br},1} \approx 330$  s, which is probably the afterglow emission. The afterglow decay from  $T_0 + 324$  s to +1.2 Ms can be fit with a broken power-law with an initial decay slope of  $\alpha_2 = 0.24 \pm 0.03$ , a break at  $t_{\text{br},2} = 3.2^{+1.2}_{-0.7}$  ks, and a postbreak slope of  $\alpha_3 = 1.22 \pm 0.03$  (we use here the notation of Nousek et al. 2006).

A power-law fit to the 0.3–10 keV spectrum from  $T_0 + 107$  s to +248 s (WT mode) gives a photon index of  $\Gamma = 2.05 \pm 0.06$  and a column density of  $(2.26 \pm 0.20) \times 10^{21} \text{ cm}^{-2}$ . The Galactic hydrogen column density in the direction of the burst is  $6.7 \times 10^{20} \text{ cm}^{-2}$ . An extrapolation backward in time of the flat afterglow component ( $\alpha_2$  segment in Fig. 3) tells us that the contribution of the underlying afterglow during this period is negligible and can safely be ignored in the spectral analysis. We also fit an absorbed single power-law model to the XRT 0.3–10 keV spectrum in PC mode (from  $T_0 + 249$  s to +1610 s). Here we found a photon index of  $\Gamma = 2.2 \pm 0.2$  and a column density of  $(1.7 \pm 0.5) \times 10^{21} \text{ cm}^{-2}$ . At later times, from  $T_0 + 6096$  s to +45,416 s, the X-ray spectrum was well described by a single power-law model with photon index  $\Gamma = 2.4 \pm 0.4$  and an absorbing column density of  $(1.9 \pm 0.8) \times 10^{21} \text{ cm}^{-2}$ .

### 2.3. *Swift* UVOT

The *Swift* Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005) began observing the field of GRB 060714 at  $T_0 + 90$  s in the settling mode and obtained the first detection in the white filter (160–650 nm) in the exposure starting at  $T_0 + 108$  s (Boyd & Marshall 2006). The position of the afterglow measured in the image from the initial exposure with the white filter is R.A. =  $15^{\text{h}}11^{\text{m}}26.444^{\text{s}}$  ( $227.8602^{\circ}$ ), decl. =  $-6^{\circ}33'58.35''$  ( $-6.5662^{\circ}$ ) (J2000.0). The uncertainty of this position is likely to be dominated by systematic errors, which we estimate to be  $\sim 0.5''$  (90% confidence radius) based on residuals when matching UVOT sources in the image to stars in the USNO B1.0 catalog (Monet et al. 2003). UVOT used the standard sequence of exposures for observing gamma-ray bursts. The sequence cycles through all seven lenticular filters with increasing exposure times as the time from the trigger increases. The afterglow was strongly detected in the white and *V* filters and weakly detected in the *B* filter. Figure 4 shows the UVOT detections and upper limits in the white, *V*, and *B* bands, using UVOT CALDB version 20061116 and correcting for galactic extinction using the extinction curve of Pei (1992) and the reddening from Schlegel et al. (1998). The count rates in the white filter were converted to equivalent *V* magnitudes using

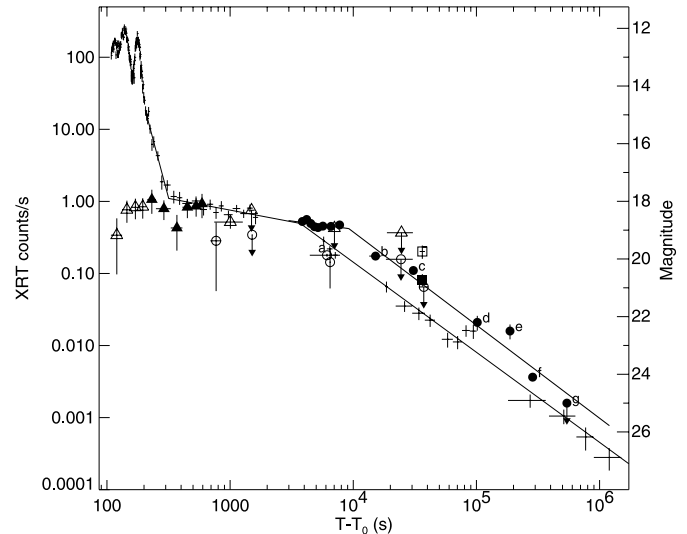


FIG. 4.—Optical measurements (*various symbols*; right-hand scale) and X-ray count rate (*plus signs*; left-hand scale) for the late-time observations. The fits to the data discussed in the text are shown as solid lines. The optical symbols are defined as follows: *filled triangles*, *V* band; *open triangles*, white; *open circles*, *B* band; *filled circles*, *R* band; *open square*, *J* band; *filled square*, *I* band. References.—*I* and *J* band: Cobb (2006); unlabeled *R* band: Asfandyarof et al. (2006); labeled points: (a) Asfandyarof et al. (2006), (b) Pavlenko et al. (2006a), (c) Jakobsson et al. (2006b), (d) Pavlenko et al. (2006b), (e) Rumyantsev et al. (2006), (f) Jakobsson et al. (2006c), (g) Jakobsson et al. (2006d). All other points are UVOT measurements. *U*- and UVW1-band upper limits are omitted for clarity. All upper limits are  $2\sigma$ .

the ratio of the average count rates in white and *V* seen in the multiple exposures between  $T_0 + 700$  s and +1582 s. Upper limits ( $2\sigma$ ) in the *U* and UVW1 bands (omitted for clarity from Fig. 4) are  $U > 18.6$  ( $667 \text{ s} < T_0 < 835 \text{ s}$ ), and UVW1  $> 19.3$  ( $643 \text{ s} < T_0 < 811 \text{ s}$ ). This lack of detection is consistent with the reported burst redshift of  $z = 2.71$  (Jakobsson et al. 2006a; see § 2.4) which shifts the Lyman edge to 338 nm, cutting out much of the *U* and all of the UVW1 band. The Lyman forest is also likely to reduce the flux in the *U* and *B* filters.

During the time period in which the X-ray light curve is showing flares followed by a steep decline, the optical light curve in the *V* band is essentially flat and at the same level as the afterglow. This tells us that the flaring activity does not manifest itself in the optical and suggests that the afterglow component dominates the optical light curve even at early times. This is consistent with what has been seen for other bursts with intense early flaring activity (for example Romano et al. 2006; Guetta et al. 2007), and for the unusual “late plateau” of GRB 070110 (Troja et al. 2007). At least during the time for which we have optical data, this burst seems to behave in a similar way to GRB 050401 (Rykoff et al. 2005) in which the optical and X-ray emission vary independently, but the prompt optical emission is consistent with a backward extrapolation of the later afterglow emission.

### 2.4. Other Observations

GRB 060714 was well observed by a large number of other telescopes with detections beginning at  $T_0 + 3860$  s (Asfandyarof et al. 2006) and continuing until  $T_0 + 3.31$  days (Jakobsson et al. 2006c). A  $2\sigma$  upper limit of  $R > 25.0$  was obtained at  $T_0 + 6.28$  days (Jakobsson et al. 2006d). Figure 4 shows the reported optical detections compared to the X-ray data. During an observation beginning 12 hr after the burst, with the FOcal Reducer and low dispersion Spectrograph for the Very Large Telescope of the European Southern Observatory, Jakobsson et al. (2006a) acquired a spectrum showing numerous absorption features which

TABLE 1  
DATA DISPLAYED IN THE TOP THREE PANELS OF FIG. 5

Time Interval	Fluence (0.3–10 keV)	Fluence (15–150 keV)	$E_{\text{pk}}$ (keV)	Power-Law Index	$E_{\text{iso}}$ ( $10^{52}$ ergs)
–13.4–18.0.....	...	$3.95^{+0.45}_{-0.89}$	$>77.6$	$1.61 \pm 0.13$	$>3.74$
70.21–86.2.....	...	$3.44^{+0.35}_{-2.45}$	$55.5 \pm 11.5$	$1.00 \pm 0.51$	$1.36^{+0.55}_{-0.29}$
86.2–102.88.....	...	$1.90^{+1.68}_{-0.49}$	$45.0 \pm 9.6$	$1.38 \pm 0.36$	$1.76^{+0.74}_{-0.39}$
107.0–121.04.....	$1.35 \pm 0.16$	$0.66 \pm 0.15$	$9.8 \pm 1.5$	$1.50 \pm 0.16$	$0.64 \pm 0.07$
121.04–159.21.....	$0.58^{+0.06}_{-0.07}$	$0.06^{+0.06}_{-0.04}$	$3.9 \pm 0.77$	$1.51 \pm 0.24$	$0.58 \pm 0.10$
159.21–199.21.....	$0.32^{+0.34}_{-0.09}$	$<0.0504$	$0.5 \pm 0.50$	$1.90 \pm 0.26$	$0.36 \pm 0.07$

NOTE.—Fluence is in units  $10^{-8}$  erg  $\text{cm}^{-2}$ .

correspond to a redshift of  $z = 2.711 \pm 0.001$  and a neutral hydrogen column density of  $(6.3 \pm 1.5) \times 10^{21}$   $\text{cm}^{-2}$ . As seen in Figure 4, the *R*-band optical light curve can be well fit to a broken power-law decay with an index  $\alpha_{R,2} = 0.23 \pm 0.13$  before  $T_0 + \sim 10^4$  s, and  $\alpha_{R,3} = 1.29 \pm 0.10$  after. These values are very similar to the decay constants for the X-ray afterglow,  $\alpha_{X,2} = 0.24 \pm 0.03$  and  $\alpha_{X,3} = 1.22 \pm 0.03$ , respectively. However, the break in the X-ray light curve occurs at least 3 ks (corresponding to a factor of  $\sim 2$  in time) earlier than the break in the *R*-band light curve.

### 3. SPECTROSCOPY AND LIGHT CURVES OF THE FLARES

There were a total of five flares detected in this burst, as seen in Figure 2. The first two were seen only in the BAT; the first was during the slew and the second during times when the XRT was observing in Imaging and Photodiode mode and no detailed spectral or temporal information is available. The third one was significant in both BAT and XRT and the fourth and fifth were seen as strong flares in the XRT, and weakly in the BAT.

In the observer frame the flares lasted from  $\sim 84$  to  $\sim 210$  s after the onset of burst emission (at  $T - 13.4$  s). Given the burst redshift of  $z = 2.71$  (a quite typical value for *Swift*), in the source frame the flares extend from  $\sim 23$  to  $\sim 56$  s after the start of emission. Although this means that the flares are relatively early as seen in the source frame, the timing of flares varies widely in the cosmological frame of GRBs, and there is no indication that absolute timing is a distinguishing characteristic of flares. Although the timing analysis described in § 3.1 and discussed in § 4 is done in the observer frame, the conclusions are all based on relative timing and do not depend on the cosmological frame chosen.

#### 3.1. Spectroscopy

All five flares were fit with a spectral model of a power law with exponential cutoff:  $F(E) = A(E/100 \text{ keV})^{-\alpha} \exp[-E(2 - \alpha)/E_{\text{pk}}]$ , where  $E$  is the photon energy,  $E_{\text{pk}}$  is the peak energy of the  $\nu F(\nu)$  spectrum,  $\alpha$  is the photon index, and  $A$  is a normalization factor. The first two were fit to BAT alone, the last three to BAT jointly with XRT. For the fourth and fifth flares inclusion of the BAT data did not significantly affect the fit. The bars at the bottom of Figure 2 indicate the time segments used to fit each of the flares. The results of the spectral fits are shown in Table 1 and in the top two panels of Figure 5. Although there is no evidence for a smooth power-law decay underlying the flares, it is possible that they overlap each other temporally. We have increased the error bars on the flux and  $E_{\text{iso}}$  values in Table 1 to account for this overlap by extrapolating the power-law fits (§ 3.2) to each flare down to zero and estimating the fraction of the flux falling outside

of the nominal start and stop times of the flare (for the upper limit), and the flux possibly due to neighboring flares (for the lower limit).

In the fits to the last three flares an absorption component was included in the model. The column densities were found to be (units  $10^{21}$   $\text{cm}^{-2}$ ), respectively for flares 3–5,  $1.91 \pm 0.43$ ,  $1.86 \pm 0.36$ , and  $1.67 \pm 0.22$ , consistent within errors to a constant value.

One can see in Figure 5 that the peak energies of the flares decrease with time and the power-law indices show a general softening of the spectra. Furthermore, the apparent linearity of the plots indicates a connection (or at least a clear trend) between the five flaring events. The time dependence of  $E_{\text{pk}}$  is well fit by a power law, with index  $-5.81 \pm 0.68$ . Similarly, the time dependence of the power-law index can be fit to a power law with index  $0.67 \pm 0.15$ .

Using the redshift  $z = 2.71$  for this burst, we extrapolate the total isotropic equivalent radiated energy,  $E_{\gamma,\text{iso}}$  (in ergs) in the range of 1– $10^4$  keV, using the definition of Amati et al. (2002). For the flares, the extrapolation fixes the  $E_{\text{pk}}$  and  $\alpha$  values derived from the cutoff power-law fits, and uses a fixed high-energy index  $\beta = -10.0$ . For the prompt emission we derive a lower limit to  $E_{\gamma,\text{iso}}$  from the lower limit to  $E_{\text{pk}}$ . The third panel of Figure 5 shows  $E_{\gamma,\text{iso}}$  as a function of time. There is a general trend toward lower total energy output of successive flares. Here a fit to a temporal decay power law gives an index of  $-1.72 \pm 0.46$ . In Figure 6 we plot  $E_{\text{pk}}$  against  $E_{\gamma,\text{iso}}$  for the flares and the prompt emission. This enables us to compare the episodes of GRB 060714 to the  $E_{\text{pk}}-E_{\gamma,\text{iso}}$  relationships found by Amati et al. (2002) and parameterized by Ghirlanda et al. (2004).<sup>7</sup> The prompt emission and the first two flares fall on or very close to the relationships, while the last three flares fall well below them. This shows that  $E_{\text{pk}}$  is falling with time more rapidly than the square of the total isotropic equivalent energy emitted in the flares,  $(E_{\gamma,\text{iso}})^2$ .

#### 3.2. Temporal Analysis

In addition to the spectral properties of the flares, the temporal properties can also help to tell us whether or not these events arise in the external shock (i.e., are afterglow emission).

In order to study the fine time structure of subpeaks within the flares, we have derived a robust method for distinguishing between a significant change in slope of the light curve (indicating the start or end of a new subpeak) and a statistical fluctuation. Using one-second binned light curves for both the BAT and XRT data, we applied an iterative method to find each significant episode (subpeak) during the times of the flares. In the first iteration,

<sup>7</sup> Since we do not see a jet break in the light curve, we are unable to constrain the  $E_{\text{pk}} - E_{\gamma}(\theta)$  relation of Ghirlanda et al. (2004).

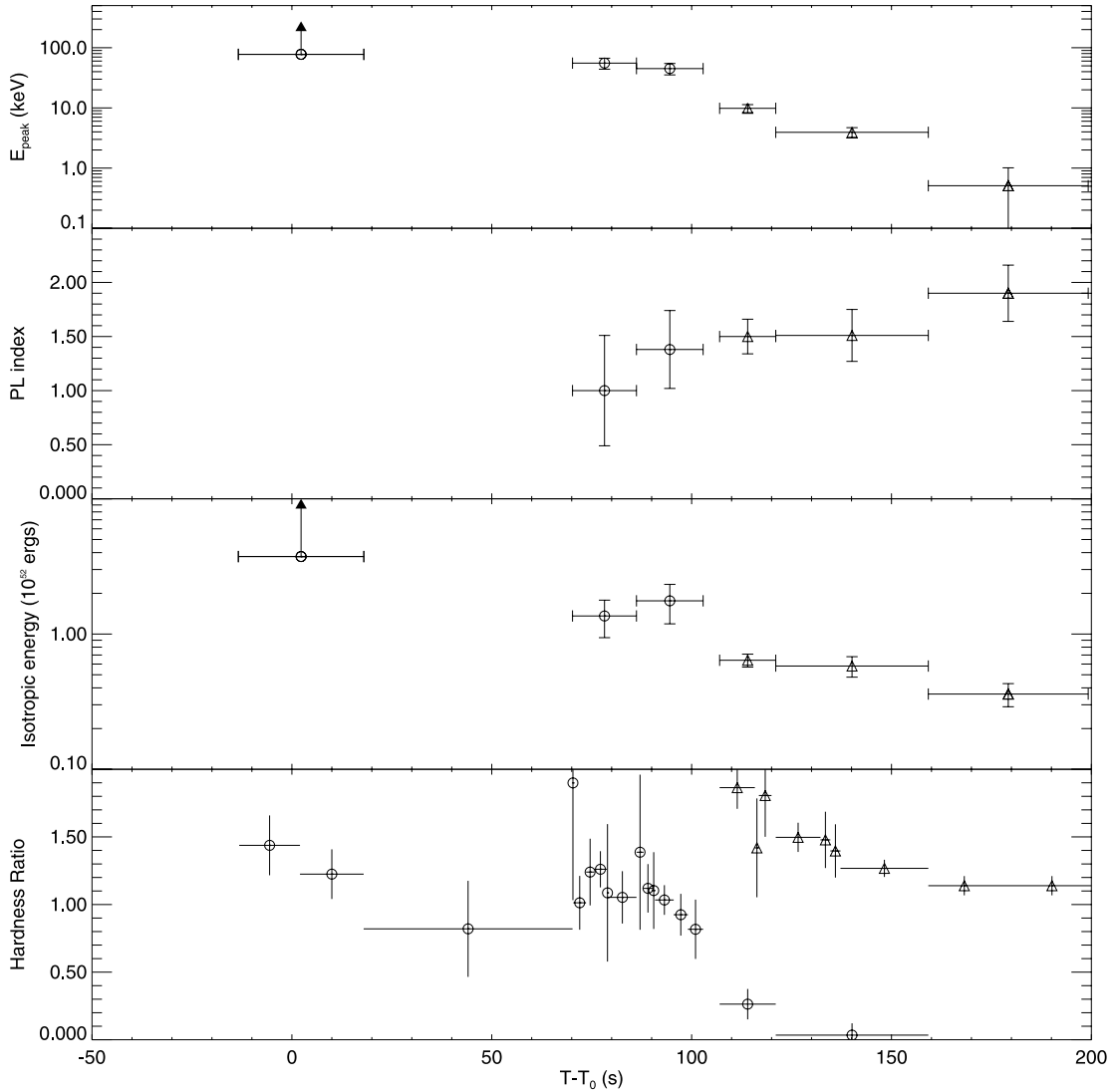


FIG. 5.—Evolution of spectral fit and energetic properties of the flares. The fits are to BAT alone (*circles*) and BAT and XRT jointly (*triangles*). We were unable to fit a cutoff power law to the prompt emission, so the points for the prompt emission show lower limits on  $E_{\text{pk}}$  and  $E_{\text{iso}}$ . The top panel shows how  $E_{\text{pk}}$  (shown in the observer frame) changes from the prompt emission through the five flares. The second panel shows the evolution of the power-law index ( $\alpha$  in the cutoff power-law fit) across the flares. Both of the two top plots clearly show a hard-to-soft spectral evolution as the flares progress. The third panel shows the time evolution of the isotropic radiated energy over the 1–10<sup>4</sup> keV energy range, indicating the flares become progressively less energetic. The data plotted in the top three panels is also given in Table 1. The bottom panel shows hardness ratios for the burst. For the prompt emission and the first four flares the flux ratio  $S(50\text{--}100\text{ keV})/S(25\text{--}50\text{ keV})$  is shown as circles. (The hardness ratio for the last flare is consistent with zero.) For the last three flares, we also show the flux ratio  $S(1.5\text{--}10\text{ keV})/S(0.3\text{--}1.5\text{ keV})$  (*triangles*).

peaks were defined as local maxima (points higher than each of their nearest neighbor points) and valleys as local minima. In successive iterations we culled the peaks by requiring that a significant peak be at least three standard deviations above the valleys on either side. By this method, each point in the light curve was assigned a specific interval, either to the rise or fall of a peak, or to the periods of slow rise ( $T < -13.4$  s) or slow decay ( $18.0\text{ s} < T < 70.2$  s or  $T > 105.4$  s for BAT; and  $T > 195.6$  s for XRT). We then fit each interval to a power law,  $\log(R)$  versus  $\log(t)$ , where  $R$  is the count rate for either BAT or XRT (depending on which flare is being analyzed) and  $t$  is the time since the burst trigger. Finally, we use these power-law fits to define the actual start, apex, and end of each subpeak (not restricted to light curve bin edges). The start of each episode ( $t_1$ ) is defined as the time at which the rising power-law segment of a peak crosses the falling power-law segment of either the preceding smooth decay or the

previous peak. Similarly, the peak time of each interval ( $t_2$ ) is the time at which the rising power-law segment of a peak meets the falling power law of the same peak. The rise time ( $\Delta t$ ) is thus defined as  $\Delta t \equiv t_2 - t_1$ , while the time associated with each rise episode is  $t \equiv (t_2 + t_1)/2$ . Thus,

$$\frac{\Delta t}{t} \equiv \frac{2(t_2 - t_1)}{(t_2 + t_1)} = \frac{\Delta t}{(t_1 + \Delta t/2)} = \frac{\Delta t}{(t_2 - \Delta t/2)}. \quad (2)$$

The conclusions drawn in § 4 do not depend critically on the exact definitions of  $t$  or  $\Delta t$ .

The episodes so defined are shown graphically in Figure 7 and their main temporal properties in Table 2. The temporal decay indices are derived in two ways, detailed in the table caption. The decay index is first calculated using the burst trigger time  $T_0$  as the reference time ( $\alpha_A$ ), which is the standard way that GRB

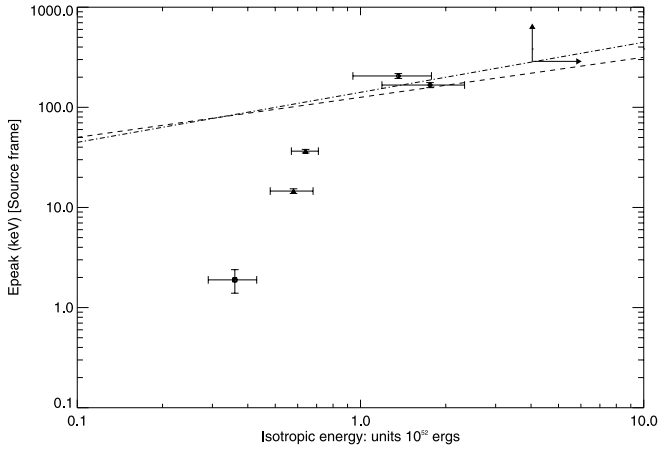


FIG. 6.—Peak energy vs. isotropic energy over the  $1\text{--}10^4$  keV energy range (the same energy range used by Amati et al. 2002). The dashed line is the fit to  $E_{\text{pk}}\text{--}E_{\text{iso}}$  derived by Ghirlanda et al. (2004) and the dot-dashed line is the fit derived by Amati et al. (2002). The time ordering of the flares goes monotonically from highest  $E_{\text{pk}}$  to lowest. The prompt emission and the first two flares detected fall on the Amati relation while the last three flares fall below.

decay indexes are calculated, and would be appropriate for the flares if they were afterglow emission. However, since the resulting values of the decay index  $\alpha_A$  are very high, corresponding to a very steep decay which is very hard to produce by the afterglow emission (Kumar & Panaitescu 2000; Nakar & Piran 2003), we also want to explore the possibility that the flares arise from late-time sporadic activity of the central source. In this case the appropriate reference time,  $t_0$ , would roughly correspond to the onset of the individual flare or subflare whose decay rate we wish to quantify ( $\alpha_B$ ). Both decay indices are shown in Table 2, although values quoted in Figure 3 are taken as the decay index  $\alpha_B$ . Even taking the second definition,  $\alpha_B$ , the decay indexes of the flares are all very steep, and except for flare 4, much steeper than either the decay of the emission just before the first flare ( $\alpha = 1.16 \pm 0.47$ ) or the decay immediately after the fifth flare ( $\alpha = 2.14 \pm 0.13$ ). The decay slope immediately after the last flare is still much steeper than the afterglow beginning at  $T + \sim 320$  s, so it is likely part of the prompt emission as well. We note, however, that  $\alpha_B$  does not exceed  $2 + \beta$  [within the statistical uncertainty, where  $F_\nu \propto \nu^{-\beta}(t - t_0)^{-\alpha}$ ], which is the steepest decay allowed by the “high-latitude” emission (Kumar & Panaitescu 2000), and thus the

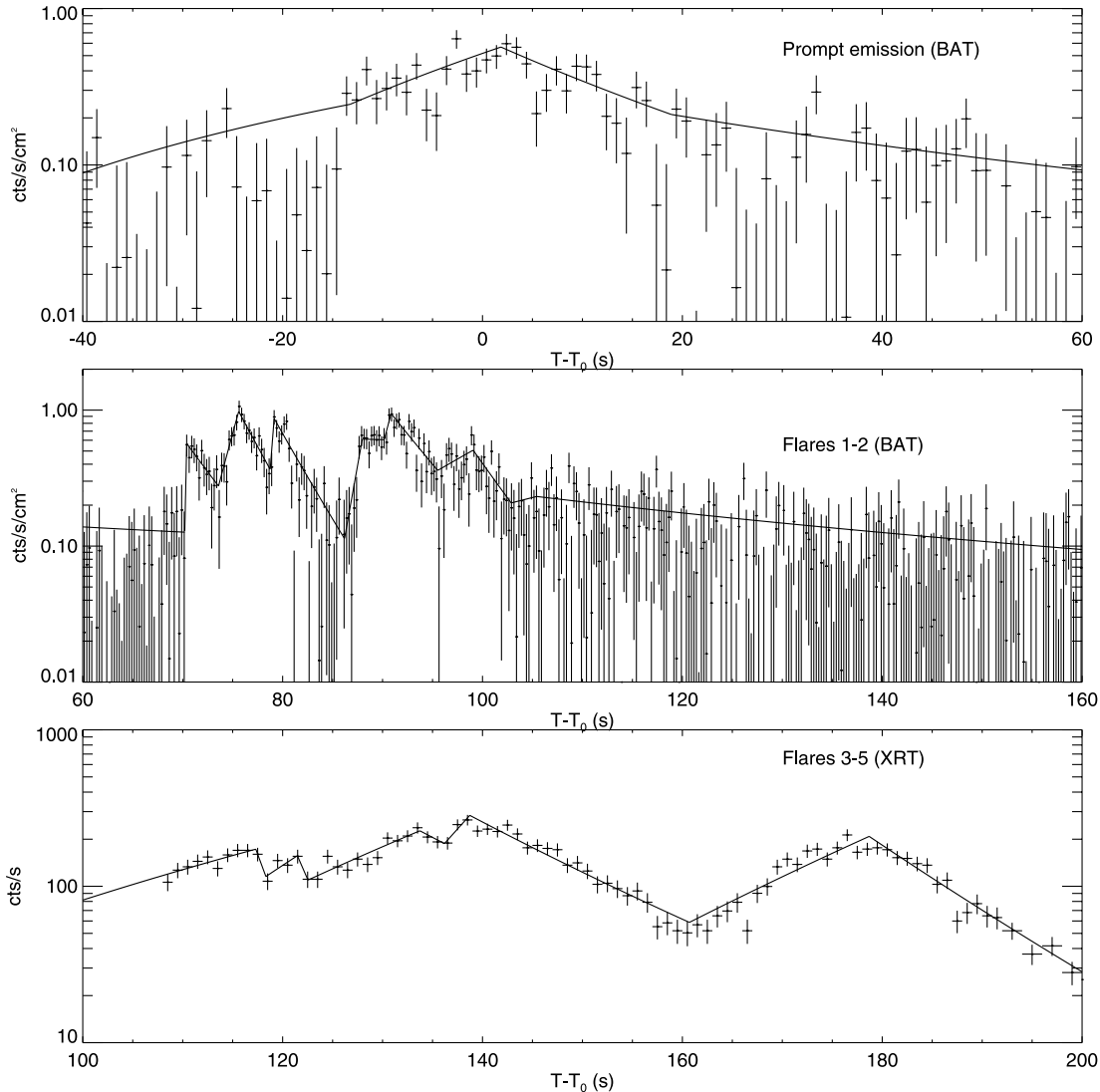


FIG. 7.—Prompt emission (*top*), BAT-detected flares (*middle*), and XRT-detected flares (*bottom*), all on the same timescale. The solid lines on the plot show the best power-law fit to each individual segment of the light curve, and the changes in slope indicate the start, apex, and end of each subpeak. The method for defining the intervals is given in the text, and decay constants are listed in Table 2. One can note the sharp temporal features (subpeaks) of the flares. It is also clear that the X-ray flares are longer than the BAT flares, a feature also seen in Romano et al. (2006) and consistent with previous results showing that the duration of pulses in prompt emission are longer at low energy than at high energy.

TABLE 2  
TEMPORAL DECAY SLOPES OF FLARES

Flare (1)	Peak (2)	Start $t_1$ (3)	Rise Time $\Delta t$ (s) (4)	Decay Index $\alpha_A$ (5)	$t_0$ for $\alpha_B$ (s) (6)	Decay Index $\alpha_B$ (7)
Prompt.....	...	-13.4	15.5	$5.4 \pm 1.1$	-13.17	$2.34 \pm 0.45$
Prompt decay .....	...	18.0	...	$2.1 \pm 0.8$	-13.17	$1.16 \pm 0.47$
1.....	1	70.2	0.19	$16.3 \pm 5.3$	70.21	$0.29 \pm 0.11$
1.....	2	73.6	2.01	$24.0 \pm 4.1$	70.21	$2.14 \pm 0.36$
1.....	3	78.8	0.39	$23.9 \pm 2.8$	70.21	$3.35 \pm 0.39$
2.....	1	86.2	1.77	$19.2 \pm 2.5$	86.2	$1.33 \pm 0.18$
2.....	2	95.5	3.54	$23.7 \pm 4.8$	86.2	$3.50 \pm 0.71$
3.....	1	102.9	2.54	$46.9 \pm 17.7$	108.5	$3.77 \pm 1.42$
3.....	2	118.3	3.14	$41.2 \pm 18.2$	108.5	$4.56 \pm 2.01$
4.....	1	122.5	11.2	$10.3 \pm 5.1$	122.54	$0.96 \pm 0.46$
4.....	2	136.2	2.52	$10.7 \pm 0.5$	122.54	$1.78 \pm 0.08$
5.....	...	160.7	18.0	$17.7 \pm 0.7$	160.71	$2.73 \pm 0.12$
Final prompt decay .....	...	195.6	...	$6.34 \pm 0.39$	160.71	$2.14 \pm 0.13$
Shallow afterglow .....	...	323.8	...	$0.31 \pm 0.17$	160.71	$0.24 \pm 0.03$
Steep afterglow .....	...	3200	...	$1.24 \pm 0.05$	160.71	$1.21 \pm 0.03$

NOTES.—Flares are numbered as in the text and Figs. 1 and 2. Times are with reference to the trigger time  $T_0$ , and the definition of the rise time is given in the text. The decay index is derived through a fit to  $R \propto (t - t_0)^{-\alpha}$ , where  $R$  is the photon event rate,  $t$  is the time, and  $t_0$  is defined as the trigger time  $T_0$  when deriving  $\alpha_A$  (col. [5]), and as the start of the particular peak or flare when deriving  $\alpha_B$  (col. [7]). The values of  $t_0$  used in the derivation of  $\alpha_B$  are shown in column (6).

decay of the flares and subflares is consistent with the expectations for late-time intermittent activity of the central source.

#### 4. DISCUSSION

##### 4.1. The External Shock

The temporal properties of the flares provide strong evidence against an external shock (i.e., afterglow) origin for them. Figure 8 shows the fractional increase in flux,  $\Delta F/F$ , versus the ratio of the rise time ( $\Delta t$ ) to the peak of each flare or subflare and the time ( $t$ ) from the GRB trigger,  $\Delta t/t$  (see eq. [2]). It can clearly be seen that large amplitude variations in the flux,  $\Delta F/F \gtrsim 1$ , occur on very short timescales,  $\Delta t/t \ll 1$ . This basically rules out an external shock origin for the flares (see, e.g., Ioka et al. 2005; Nakar 2006; Lazzati & Perna 2007). We also note that the flares are very different from the smooth, late-time tail emission in the 20–100 keV band which was observed to follow many of the bursts detected by the Burst and Transient Source Experiment (BATSE; Connaughton 2002). The tail emission is temporally much smoother than the flares of GRB 060714 and at a much lower level (as a ratio to the peak of the prompt emission). Also, Giblin et al. (2002) identify a subset of the BATSE bursts that have high-energy decay emission consistent with forward external shocks. Although it is below detectability for BAT, it is possible that the tail emission is seen after the last flare in the  $\alpha_1 = 2.14$  decay segment (Fig. 3). This decay index is consistent with the average temporal decay index reported for BATSE tail emission,  $-2.03 \pm 0.51$  (Giblin et al. 2002).

The major possible sources of variability in the afterglow light curves (i.e., in the emission from the external shock) are (1) a variable external density (Wang & Loeb 2000; Lazzati et al. 2002; Nakar et al. 2003), (2) a “patchy shell,” i.e., angular inhomogeneity within the outflow (Kumar & Piran 2000b; Nakar et al. 2003), and (3) “refreshed shocks,” i.e., relatively slow shells that were ejected from the central source toward the end of the prompt emission and catch up with the afterglow shock as the latter decelerates to a Lorentz factor slightly lower than that of the shells (Rees & Mészáros 1998; Kumar & Piran 2000a). Such a sharp ( $\Delta t/t \ll 1$ ) large amplitude ( $\Delta F/F \gtrsim 1$ ) rise in the observed flux, as we

find for GRB 060714 (see Fig. 8), cannot be caused by a sudden increase in the external density (Nakar & Granot 2006). In addition, a “patchy shell” produces  $\Delta t/t \sim 1$  (Nakar & Oren 2004) and cannot account for the observed  $\Delta t/t \ll 1$ , since new “bright spots” in the outflow become visible (i.e., enter the observed region of angle  $\sim 1/\gamma$  around the line of sight) gradually, on the dynamical time ( $\Delta t \sim t$ ). Finally, “refreshed shocks” produce  $\Delta t/t \sim 1$  before the jet break time, when the rise time  $\Delta t$  is dominated by the angular time  $t_\theta \approx R/2c\gamma^2$ . After the jet break time, the angular

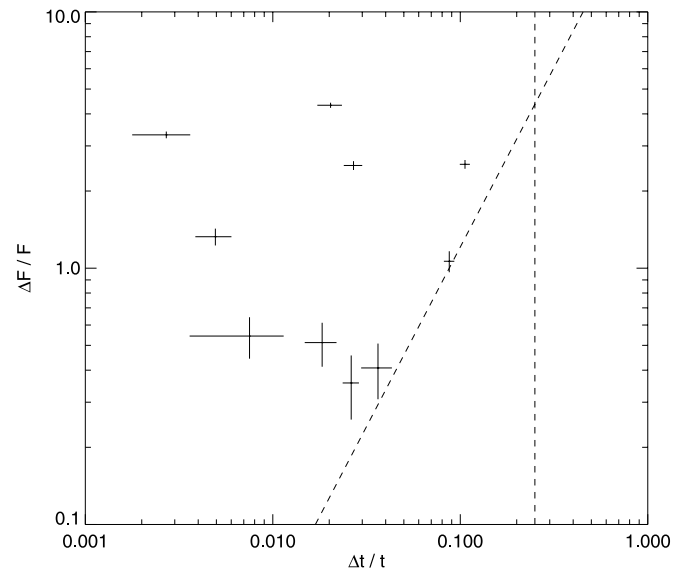


FIG. 8.—Plot of  $\Delta t/t$  vs.  $\Delta F/F$ . The flux ratio  $\Delta F/F$  is derived as  $\Delta F = [F(t_2) - F(t_1)]$  and  $F = F(t_1)$ , where  $F(t_1)$  and  $F(t_2)$  are the flux at the start and top of each peak, respectively. In this notation  $\Delta F/F = 1$  means a doubling of the flux. This figure shows that for all peaks  $\Delta F/F \sim 1$  while  $\Delta t/t \ll 1$ . The area to the right of the dashed lines indicates the kinematically allowed region for afterglow variability derived by Ioka et al. (2005). The vertical line indicates that refreshed shocks cannot make a bump with  $\Delta t < t/4$ . Ioka et al. (2005) also argue that ambient density fluctuations cannot make a bump in afterglow light curves larger than the limit indicated by the diagonal line.



time is  $t_\theta \approx R\theta_j^2/2$  (where  $\theta_j$  is the half-opening angle of the jet), and it soon becomes smaller than the radial time  $t_r \approx R/10c\gamma^2$  (since  $\theta_j$  remains close to its initial value,  $\theta_0$ , as long as the jet is relativistic; Granot 2006), so that the rise time  $\Delta t$  becomes dominated by the radial time (Granot et al. 2003). However, even in this case  $\Delta t/t \gtrsim 0.2$ , which cannot explain the values of  $\Delta t/t < 0.1$ , in some cases even as low as  $\Delta t/t \lesssim 10^{-2}$ , that we obtain in our analysis.

#### 4.2. Other Possible Causes for the Flares

Now that we have effectively excluded an external shock origin for the flares, we explore other possible explanations. These involve sporadic late-time dissipation events which are a result of either (1) early-time activity of the central source on a timescale comparable to the duration of the prompt GRB emission, or (2) late-time intermittent activity of the central source, which is rather directly reflected in the observed times of the flares. Both types of models may in principal be applicable both for the prompt GRB emission and for the flares, due to their roughly similar observed properties. Thus, we also wish to address the similarities and differences in the observed temporal and spectral properties of the flares and the prompt emission.

Models in the literature that can be included in the first of the two above classes include both emission powered by sporadic magnetic dissipation events within the outflow, possibly induced by its interaction with the external medium (Lyutikov & Blandford 2002; Giannios 2006; Thompson 2006), and late-time internal shocks between shells with a small relative velocity (e.g., Barraud et al. 2005; Burrows et al. 2007). In the former models the temporal and spectral properties of the emission have not yet been worked out in detail, so direct comparison to observations is not possible at this stage. We now briefly address the latter model.

#### 4.3. Internal Shocks with Small Contrast in the Lorentz Factor

In this scenario the difference in the Lorentz factors of the colliding shells,  $\Delta\gamma$ , is much smaller than their typical Lorentz factor  $\gamma$ , i.e.,  $\Delta\gamma \ll \gamma$ . For convenience, we provide most of the relevant results here, while a detailed derivation of these results as well as some relevant (but somewhat more technical) discussion is provided in the Appendix. In this picture, later collisions correspond to a smaller  $\Delta\gamma/\gamma$ , occurring at an observed time  $t_{\text{fl}}$  and with a duration  $\Delta t_{\text{fl}}$  which satisfy

$$t_{\text{fl}} \sim t_{\text{ej}} + \frac{\gamma}{\Delta\gamma} \Delta t_{\text{ej}}, \quad \Delta t_{\text{fl}} \sim \frac{\gamma}{\Delta\gamma} \Delta t_{\text{ej}} \sim t_{\text{fl}} - t_{\text{ej}}, \quad (3)$$

where the first and second shells are ejected at times  $t_{\text{ej}}$  and  $t_{\text{ej}} + \Delta t_{\text{ej}}$  with Lorentz factors  $\gamma$  and  $\gamma + \Delta\gamma$ , respectively. This makes it hard to account for the short timescale variability  $\Delta t/t \ll 1$ , unless the colliding shells were ejected from the source at a time  $t_{\text{ej}}$  after the GRB trigger that is much closer to the observed time of the flare  $t_{\text{fl}}$  than to the GRB trigger  $t = 0$  (since  $\Delta t/t = \Delta t_{\text{fl}}/t_{\text{fl}} \sim 1 - t_{\text{ej}}/t_{\text{fl}}$ ). However, this corresponds to models of class 2 from § 4.2 (where the central source is active at late times, close to the time of the observed flares), rather than class 1. Lazzati & Perna (2007) come to a similar conclusion.

In the latter case, which corresponds to class 2, one can in principal account for the temporal properties of the flares. We also wish to examine whether their spectral properties and energetics can naturally be reproduced. In this picture the shells collide at a radius

$$R_{\text{IS}} \approx \frac{\gamma}{\Delta\gamma} \gamma^2 c \Delta t_{\text{ej}} \quad (4)$$

(the subscript ‘‘IS’’ is for internal shocks), which is larger by a factor of  $\sim \gamma/\Delta\gamma \gg 1$  (for the same average  $\gamma$ ) compared to internal shocks with a reasonably large contrast in the Lorentz factor,  $\Delta\gamma \gtrsim \gamma$ . For a reasonably large contrast in the Lorentz factor ( $\Delta\gamma/\gamma \gtrsim 1$ ) the peak of the  $\nu F(\nu)$  spectrum,  $E_{\text{pk}}$ , typically corresponds to  $h\nu_m$ , where  $\nu_m$  is the synchrotron frequency of the relativistic electrons with the minimal random Lorentz factor in the power-law distribution of energies. However, for low contrast internal shocks ( $\Delta\gamma/\gamma \ll 1$ ),

$$\nu_m \propto \left(\frac{\Delta\gamma}{\gamma}\right)^5 L_{\text{iso}}^{1/2} R_{\text{IS}}^{-1} \propto \left(\frac{\Delta\gamma}{\gamma}\right)^6 L_{\text{iso}}^{1/2} \gamma^{-2} (\Delta t_{\text{ej}})^{-1}, \quad (5)$$

where  $L_{\text{iso}}$  is the isotropic equivalent kinetic luminosity of the outflow, under the standard assumptions that the fractions of the internal energy behind the shock in the relativistic electrons ( $\epsilon_e$ ) and in the magnetic field ( $\epsilon_B$ ) are constant. That is,  $\nu_m$  decreases very rapidly for a small contrast  $\Delta\gamma/\gamma$ . On the other hand, the cooling break frequency  $\nu_c$  increases as  $\Delta\gamma/\gamma$  decreases,

$$\nu_c \propto \left(\frac{\Delta\gamma}{\gamma}\right)^{-3} L_{\text{iso}}^{-3/2} R_{\text{IS}} \gamma^6 \propto \left(\frac{\Delta\gamma}{\gamma}\right)^{-4} L_{\text{iso}}^{-3/2} \gamma^8 \Delta t_{\text{ej}}. \quad (6)$$

Therefore, for  $\Delta\gamma/\gamma \ll 1$ ,  $\nu_c > \nu_m$  and there is slow cooling, i.e.,  $E_{\text{pk}} = h\nu_c$  rather than  $h\nu_m$ .

For a reasonable value of the magnetic field that is advected with the outflow from the central source, such a field would dominate over a subequipartition shock-generated field in the shocked regions of the colliding shells (see the Appendix for details). In that case  $\nu_m/\nu_c$  scales ‘‘only’’ as  $(\Delta\gamma/\gamma)^6$ , instead of  $(\Delta\gamma/\gamma)^{10}$  for a field that is a constant fraction of the equipartition value, which was assumed above. Since this is still a very high power of  $\Delta\gamma/\gamma$ , this does not change the main conclusions.

The very strong dependence of  $\nu_m/\nu_c$  on  $\Delta\gamma/\gamma$  further decreases the radiative efficiency, which is already low for  $\Delta\gamma/\gamma \ll 1$ , since the fraction of the total energy of the colliding shells that is converted into internal energy (out of which the fraction that goes into relativistic electrons,  $\epsilon_e$ , may be mostly radiated away for  $\nu_c < \nu_m$  but not for  $\nu_c > \nu_m$ ) is given by

$$\epsilon \approx \frac{x}{2(1+x)^2} \left(\frac{\Delta\gamma}{\gamma}\right)^2 \leq \frac{1}{8} \left(\frac{\Delta\gamma}{\gamma}\right)^2, \quad (7)$$

where  $x$  is the ratio of the rest masses of the two colliding shells (for a fixed contrast of the Lorentz factor,  $\Delta\gamma/\gamma$ , the efficiency  $\epsilon$  is maximal for equal mass shells,  $x = 1$ ). For GRB 060714 the combined  $E_{\gamma,\text{iso}}$  of the five flares is comparable to that of the prompt emission, and that of individual flares is at most 1 order of magnitude smaller. This suggests that the kinetic energy that remains in the colliding shells that produce the flares in this scenario is much larger than that of the original shells that produced the prompt emission. This would result in very significant episodic energy injection into the afterglow shock, i.e., ‘‘refreshed shocks,’’ which are inconsistent with the temporal properties of GRB 060714 (and may prove problematic for most *Swift* GRBs with X-ray flares). Furthermore, since the total  $E_{\gamma,\text{iso}}$  of the flares is  $\sim 10^{52.5}$  erg, such an extremely inefficient emission would imply a huge remaining isotropic equivalent kinetic energy, in excess of  $10^{55.5}$  erg for  $\Delta\gamma/\gamma \lesssim 0.1$ , which would imply a very large total kinetic energy ( $\gtrsim 10^{53}$  erg), even when corrected for the fractional solid angle occupied by the jet ( $f_b \gtrsim 10^{-2.5}$ ), given that there is no sign of a jet break at least until  $\sim 10^6$  s.

#### 4.4. Internal Shocks with Reasonably Large Contrast in the Lorentz Factor

We now examine the more popular version of the internal shocks model, where the difference in the Lorentz factor of the colliding shells,  $\Delta\gamma$ , is of the order of their average Lorentz factor  $\gamma$ , i.e.,  $\Delta\gamma \gtrsim \gamma$ . In this case the observed time of the flares reflects the time in which the colliding relativistic shells were ejected from the source (Kobayashi et al. 1997; Nakar & Piran 2002), thus requiring intermittent late-time activity of the central source (Burrows et al. 2005b). Such a sporadic late-time activity of the central source may arise (e.g., Perna et al. 2006) by infall of material into the central black hole from instabilities in an accretion disk, or by late-time fallback of material in the collapsar model (e.g., MacFadyen et al. 2001). Fan & Wei (2005) show that this model is consistent with X-ray flares in a number of different bursts.

In this scenario the radiative efficiency may be reasonably high (but still typically  $\lesssim 10\%$ ), and  $E_{\text{pk}}$  is usually given by  $h\nu_m$ . All of the equations of § 4.3 still remain valid, up to a factor of order unity, under the substitution  $\Delta\gamma/\gamma = 1$ . Thus,  $\Delta t_{\text{fl}} \sim \Delta t_{\text{ej}}$  and  $E_{\text{pk}} \propto L_{\text{iso}}^{1/2} \gamma^{-2} (\Delta t_{\text{ej}})^{-1} \propto L_{\text{iso}}^{1/2} \gamma^{-2} (\Delta t_{\text{fl}})^{-1}$ . Figure 9 shows that the rise time  $\Delta t \sim \Delta t_{\text{fl}}$  increases with time (by about 2 orders of magnitude), while  $\Delta t/t$  increases by a somewhat smaller factor (but still a factor of  $\sim 30$  over less than a factor of 3 in time). This alone can roughly account for the decrease in  $E_{\text{pk}}$  (see upper panel of Fig. 5), which decreases by about 2 orders of magnitude, similar to the increase in  $\Delta t_{\text{fl}}$ . Since for each flare  $L_{\text{iso}} \sim E_{\gamma, \text{iso}}/\Delta t_{\text{fl}}$ , and since  $E_{\gamma, \text{iso}}$  of the individual flares decreased by about 1 order of magnitude, we can infer that  $L_{\text{iso}}$  decreased by about 3 orders of magnitude, which requires  $\gamma$  to decrease by a factor of  $\sim 10^{3/4} \sim 5-6$ . Since  $R_{\text{IS}} \sim \gamma^2 c \Delta t_{\text{ej}} \sim \gamma^2 c \Delta t_{\text{fl}}$ , this implies a modest increase in  $R_{\text{IS}}$  by a factor of  $\sim 3$  (since  $\gamma^2$  decreased by a factor of  $\sim 30$  while  $\Delta t_{\text{fl}}$  increased by a factor of  $\sim 100$ ).

#### 4.5. Possible Relation to Models for the Late-Time Central Source Activity

The sharpness of the peak features can be seen in Figure 9 in which the rise time  $\Delta t$  and the ratio  $\Delta t/t$  are plotted against the time since the trigger. There is a tendency for peaks to become less sharp (increasing  $\Delta t$ ) with time. This trend is consistent with the viscous disk evolution model discussed by Perna et al. (2006) in which both the accretion timescale  $\Delta t$  and the arrival time  $t$  depend on the radial location of the accreting material within the accretion disk. Kocevski et al. (2007) show that the correlation of broader pulse durations with time holds in general even among flares from different GRBs, supporting the idea that later flares are coming from larger radius shells. The lower panel in Figure 9 shows that even for the late flares with longer rise times, that  $\Delta t/t$  remains very small,  $\lesssim 0.1$  for all peaks, although  $\Delta t/t$  tends to increase with time (it reaches values  $< 10^{-2}$  at early times).

The distribution of  $\Delta t/t$  values for GRB 060714 can be compared to the statistical samples of flares presented by Chincarini et al. (2007) and Burrows et al. (2007). We see that most of the points in our  $\Delta t/t$  distribution are consistent with the Chincarini et al. (2007) sample, while the three points with  $\Delta t/t < 0.01$  lie outside the distribution. This is explained by the difference between our definition of  $\Delta t$  (rise time) and that used by Chincarini et al. (2007;  $\sigma$  of a Gaussian fit to the peak). Although these measures are of the same order of magnitude, our definition leads to very small values of  $\Delta t/t$  for those peaks with fast rises and slower decays, and in general a broader distribution than seen by Chincarini et al. (2007). Given the asymmetric shape of many of the peaks, the rise time may be a truer measure of the variability, since the width can be skewed by a slow decay. Burrows et al.

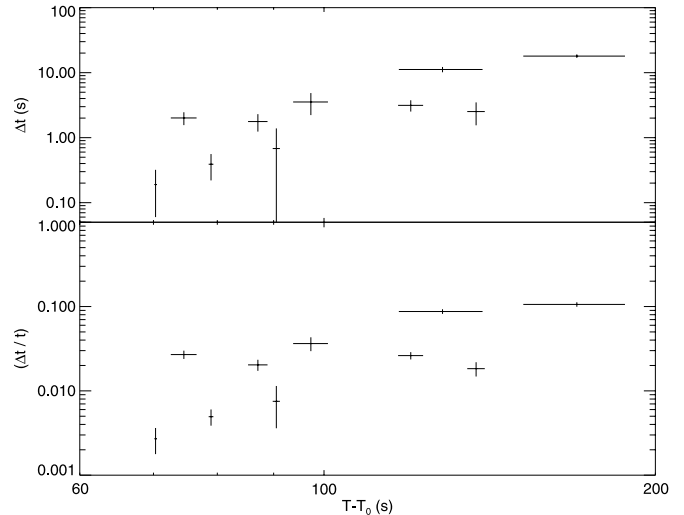


FIG. 9.—  $\Delta t$  (rise time to the peak) and  $\Delta t/t$  vs. time since the GRB trigger for each peak in each of the flares. Note that the plot is log-log. The quantities  $\Delta t$  and  $t$  are defined in the text. Although there is some scatter there is a general trend for both  $\Delta t$  and  $\Delta t/t$  to increase with  $t$  for the flares. A fit to  $\Delta t$  vs. time (top) gives a slope of  $4.0 \pm 0.9$ . It is also quite clear that for all peaks in the flares, that  $\Delta t/t \ll 1$ .

(2007) show  $\Delta t_{\text{rise}}/t$ , where  $\Delta t_{\text{rise}}$  is defined as the time between when the power law crosses the underlying afterglow and the peak time, a definition which would lead to somewhat larger values of  $\Delta t_{\text{rise}}/t$  than ours. Their distribution, however, has a median value  $\sim 10$  times larger than ours, indicating that the time structure in GRB 060714 is unusually sharp compared to most other flares. The analysis of Kocevski et al. (2007) also shows that GRB 060714 has shorter flare durations and rise times than most bursts. Alternatively, it could be that we find significant structure on smaller timescales than in other works because we are analyzing brighter flares with better photon statistics. We are also looking at substructure in the flares, as is often done with the prompt emission, in which significant temporal structure is usually found down to the smallest timescale that can be measured (which is limited either by photon statistics or the temporal resolution of the instrument).

The successive flares in GRB 060714 are each spectrally softer than the preceding flare, as seen in the top panel of Figure 5. The spectral softening of the flares is supportive of models in which multiple masses accrete onto a central black hole at successively later times. King et al. (2005) discuss a model where the collapse of a rapidly rotating stellar core leads to fragmentation and the formation of multiple compact objects which accrete onto the central black hole on timescales which depend on the orbital radii and fragment masses. King et al. (2005) and Burrows et al. (2005b) suggest that successively later accretion events occur in cleaner, lower density environments, since earlier jets would have excavated channels through the progenitor star. This suggests that later outflows would have lower baryon loading and hence higher  $\gamma$ . King et al. (2005) also suggest that tidal effects may smooth later accretion events, lengthening  $\Delta t_{\text{ej}}$ . Both increasing  $\gamma$  and increasing  $\Delta t_{\text{ej}}$  would lead to a reduction in  $E_{\text{pk}}$  as a function of time (see § 4.4). Note that  $E_{\text{pk}}$  for the prompt emission is slightly higher than  $E_{\text{pk}}$  for the first flare, which would be expected since the initial collapse should have the lowest bulk Lorentz factor. However, as demonstrated in § 4.4, while Figure 9 indeed shows that  $\Delta t \sim \Delta t_{\text{fl}}$  increases with time, we find that  $\gamma$  should have *decreased* in time (by a factor of  $\sim 5-6$ ) rather than increased with time (for the standard internal shocks model), as expected in the above model.

As can be seen in the third panel of Figure 5,  $E_{\gamma, \text{iso}}$  decreases with time roughly as  $\sim t^{-1.7}$ , and  $L_{\text{iso}}$  decreases roughly as  $t^{-3}$ . This is a steeper decline than the expected late-time accretion rate due to fallback in the collapsar model,  $\dot{M}_{\text{acc}} \propto t^{-5/3}$  (e.g., MacFadyen et al. 2001), and in fact drops roughly as  $\dot{M}_{\text{acc}}^2$ , suggestive of a relativistic outflow powered by neutrino-antineutrino annihilation, where  $L_{\text{iso}} \propto L_{\nu}^2 \propto \dot{M}_{\text{acc}}^2$  (this is, of course, highly speculative at this stage). Furthermore, such a steep decay of  $L_{\text{iso}}$  is much steeper than  $\propto t^q$  with  $q > -1$  that is required in order to account for the flat decay phase (Nousek et al. 2006). Although the latter requires a temporally smooth outflow, and the flares require intermittent source activity, it is hard to see how the overall temporal decay of such a smooth component and a variable component would be that different.

#### 4.6. Similarities and Differences between the Flares and the Prompt Emission

A striking feature of the spectroscopic results is that not only is  $E_{\text{pk}}$  declining with each flare, but the low-energy spectral index  $\alpha$  is increasing (second panel of Fig. 5), meaning that the flares are becoming successively softer with time. This is consistent with the third panel of Figure 5 which shows the total isotropic energy is decreasing with time. Hard-to-soft spectral evolution is commonly seen in the prompt emission of GRBs (Band & Ford 1998; Nemiroff et al. 1994), and the bottom panel of Figure 5 shows this trend very clearly for the period before the start of the first flare (first three points). For the flares, not only is there a softening from flare to flare, but *within* each of the first four flares there is a tendency for the spectrum to soften as well. That this well-established feature of the prompt emission of GRBs is seen within and across the flares favors similar origins for the flares and the prompt emission. Butler & Kocevski (2007) have shown for a sample of 27 *Swift*-detected GRB flares, that flares exhibit significant hardness-intensity and hardness-fluence correlations which match closely the correlations observed for GRBs. They attribute this hardness evolution to an evolving  $E_{\text{pk}}$ . The hardness ratio  $H \equiv S(50\text{--}100 \text{ keV})/S(25\text{--}50 \text{ keV})$  is close to unity for the prompt emission and the first two flares, so all three of these episodes fall well within the distribution of long bursts in a GRB hardness-duration diagram (see Roming et al. 2006 for a recent BAT hardness-duration distribution plot). If the overall spectral shape of the flares remains roughly the same, we would expect the hardness ratio  $H$  to fall dramatically as  $E_{\text{pk}}$  shifts downward through the BAT energy range (*top panel*, Fig. 5), since the BAT spectral index would shift from the super- $E_{\text{pk}}$  value of  $\sim 1$  to the sub- $E_{\text{pk}}$  value of  $\sim 2.5$ . This is indeed what we see in the bottom panel of Figure 5, supporting a common origin for the flares.

Another interesting effect is seen in Figure 6. Here we see that the prompt emission and the first two flares show a relationship between  $E_{\text{pk}}$  and  $E_{\gamma, \text{iso}}$  quite consistent with the relationships found by Amati et al. (2002). This supports a similar mechanism for these flares and for the prompt emission, since it suggests that these flares are spectrally and energetically like weak, low- $E_{\text{pk}}$  bursts. The last three flares fall well below the relations, since for the succession of flares  $E_{\text{pk}}$  is falling more quickly than  $E_{\gamma, \text{iso}}$ , with these flares remaining relatively energetic ( $E_{\gamma, \text{iso}} > 10^{51}$  erg, even as  $E_{\text{pk}}$  decreases to  $\lesssim 1$  keV). This argues against a similar origin for these two flares and the prompt emission (especially since almost all known outliers to the Amati relation are on the other side of it, i.e., with a higher  $E_{\text{pk}}$  for their  $E_{\gamma, \text{iso}}$  than expected by this relation, while here the situation is the opposite), although there are still possible ways around this. Alternatively, one could certainly argue that such a wide dispersion within a single burst over a wide range of energies should call for a reevaluation of the Amati

relationship. Although the  $E_{\text{pk}}\text{--}E_{\gamma, \text{iso}}$  relations have been shown to hold for many X-ray flashes (e.g., Sakamoto et al. 2006), it is much less clear whether the relations should hold for late-time flares or individual peaks within bursts.

The time structure of the flares is quite similar to that of the prompt emission. All of the flares show structure on timescales of  $\sim 10^{-1}\text{--}10$  s within an overall envelope of duration  $\sim 10\text{--}50$  s. The prompt emission falls within a  $\sim 30$  s envelope, and although the subpeaks in the prompt emission are not formally significant, there is a suggestion of structure on shorter timescales, especially in the 50–100 keV band (middle panel of Fig. 1). Certainly short timescale variations in the prompt emission are a common feature of GRBs.

## 5. CONCLUSIONS

The temporal properties of the series of five flares in the long gamma-ray burst GRB 060714 provide strong evidence against an external shock (or a long-lived reverse shock) origin for these X-ray flares and are consistent with sporadic late-time activity of the central source. The strongest argument against an external shock origin of the flares is that large amplitude variations in flux ( $\Delta F \gtrsim F$ ) occur on very short timescales ( $\Delta t/t \ll 1$ , where initially  $\Delta t/t \lesssim 10^{-2}$ , while for all flares or subflares  $\Delta t/t < 0.1$ ; see Figs. 8 and 9). As discussed in § 4.1, this cannot be reasonably accounted for by emission from the forward shock, and similar considerations apply also for a long-lived reverse shock.

In the context of the internal shocks model, we show that the temporal properties of the flares ( $\Delta t/t \ll 1$ ) exclude scenarios where the colliding shells are ejected from the source well before the observed times of the flares (see § 4.3), and require instead intermittent late-time activity of the central source. Even in the latter picture, an internal shocks model with small contrast in the Lorentz factor is inconsistent with the observations (see § 4.3), for the following reason. The large  $E_{\gamma, \text{iso}}$  of the five flares, together with the small efficiency of such a model in converting the bulk kinetic energy into the observed radiation, requires that a large amount of kinetic energy remain in the shells, a condition that would unavoidably produce very prominent “refreshed shocks.” Such episodic energy injections into the afterglow shock are, however, inconsistent with the temporal properties of the smooth X-ray (and optical) light curve that follows the flares.

An internal shocks model involving sporadic late-time activity of the central source and a reasonably large contrast in the Lorentz factors of the colliding shells (§ 4.4) is more consistent with the data. This type of model can avoid prominent “refreshed shocks,” in addition to being able to account for both the observed temporal properties of the flares and the decrease with time of their  $E_{\text{pk}}$  and  $E_{\gamma, \text{iso}}$ . Although the data from GRB 060714 are not sufficient for us to conclusively discriminate between particular models of late-time intermittent activity of the central source (§ 4.5), they can start testing and perhaps even eventually discriminate between the different models. For example, the viscous disk model (Perna et al. 2006) can in principal explain the trend of peaks becoming less sharp with increasing time. The simplest expectations of fragmentation models (King et al. 2005; Burrows et al. 2005b), however, are inconsistent with the decrease in the Lorentz factor  $\gamma$  that follows from the time decay of  $E_{\text{pk}}$  and  $E_{\gamma, \text{iso}}$  in the internal shocks model. Moreover, the decline in  $E_{\gamma, \text{iso}}$  is steeper than what would be expected from fallback in the collapsar model (MacFadyen et al. 2001), but suggestive of a relativistic outflow powered by neutrino-antineutrino annihilation.

Some evidence in favor of a common origin for the flares and the prompt emission is provided by the spectral and temporal similarities of these components. As in the prompt emission, there is

a clear spectral softening as the flares progress, as well as within most of the flares. Furthermore, both the prompt emission and the flares show time structure on the scale of  $\sim 1$  s within an overall envelope of duration  $\sim 10$  s. On the other hand, an argument against a common origin is the inconsistency of the final three flares with the Amati et al. (2002) relation, although it is not well-established that this relation should hold for late-time flares.

After the fifth and final flare, GRB 060714 showed typical afterglow time profiles consisting of three separate power-law segments (Fig. 3). This part of the light curve is a nice example of the “canonical” afterglow light curve found by *Swift* (Nousek et al. 2006; Panaitescu et al. 2006; Zhang et al. 2006). This burst was well observed at late times in the optical (Fig. 4) and the optical light curve shows both similarities and differences with respect to the X-ray light curve. The first optical observations showed emission at a typical value for an optical afterglow in the *Swift* era ( $V = 18.6$  at  $\sim 200$  s), and the optical magnitude remained roughly constant out to at least  $T_0 + 7700$  s, with no indication of an optical counterpart to any of the flares. Similar to the X-ray light curve, the  $R$ -band light curve also had a break to a steeper temporal decay, although the optical break occurred about a factor of  $\sim 2$  in time later than the X-ray break. Both before and after the break, the X-ray and  $R$ -band power-law temporal decay indices were quite similar. This suggests a similar origin for the late-time X-ray and optical emission: most likely afterglow emission from the forward shock, probably with some contribution from a long-lived reverse shock before and around the time of the break, which might potentially account for the difference in the break times between the optical and the X-rays.

The subject of X-ray flares in GRBs is an important one and a number of recent papers on *Swift* bursts have discussed flares, leading to a growing consensus that flares reflect late-time activity of the central source. Some important examples are Falcone et al. (2006; the giant flare of GRB 050502B), Guetta et al. (2007; GRB 050713A), and Burrows et al. (2007) and Chincarini et al. (2007) on the analysis of a statistical sample of *Swift* flares. This paper adds important new observational results and conclusions to the existing body of literature on flares. GRB 060714 contains an unusually large number of well-monitored flares in a single event, and our interpretation of the timing and energetics of these flares not only provides strong evidence against an external shock or a long-lived reverse shock model, but allows us to favor the model of late-time activity of the central source and a large contrast in the Lorentz factor of the colliding shells over an internal shocks model with a small contrast in the Lorentz factors and refreshed shocks. This event provides the best evidence to date of a continuous and gradual transition in the spectral and temporal properties of the prompt emission and flares, which is very suggestive of a common origin.

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## APPENDIX

### DERIVATION OF THE EQUATIONS IN § 4.3

Here we provide a derivation of the equations for internal shocks with a small contrast in the Lorentz factor, which appear in § 4.3. Consider two shells, where the (back edge of the) first shell (subscript “1”) is ejected from the source at (lab-frame) time  $t_1 = t_{ej}$  with Lorentz factor  $\gamma_1 = \gamma$  and rest mass  $m_1$ , while the (front edge of the) second shell (subscript “2”) is ejected at  $t_2 = t_{ej} + \Delta t_{ej}$  with a Lorentz factor  $\gamma_2 = \gamma + \Delta\gamma$  and rest mass  $m_2$ . We are interested in the limit of low contrast in the Lorentz factors of the two shells,  $\Delta\gamma/\gamma \ll 1$ , and provide below approximate expressions which are valid in that limit. The two shells collide at a lab frame time  $t_{IS}$  and a radius  $R_{IS}$  which satisfy  $R_{IS} = R_1(t_{IS}) = R_2(t_{IS})$ , where  $R_1(t) = \beta_1 c(t - t_{ej})$  and  $R_2(t) = \beta_2 c(t - t_{ej} - \Delta t_{ej})$ , so that  $t_{IS} = t_{ej} + \beta_2 \Delta t_{ej} / (\beta_2 - \beta_1)$  and

$$R_{IS} = \frac{\beta_1 \beta_2 c \Delta t_{ej}}{\beta_2 - \beta_1} \cong \frac{2\gamma_1^2 c \Delta t_{ej}}{1 - (\gamma_1/\gamma_2)^2} \approx \frac{\gamma}{\Delta\gamma} \gamma^2 c \Delta t_{ej}, \quad (A1)$$

where the “ $\cong$ ” relation is valid for  $\gamma_1, \gamma_2 \gg 1$ , while the “ $\approx$ ” relation also requires  $\Delta\gamma/\gamma \ll 1$ .

The observed time corresponding to the onset of the resulting spike in the light curve (or “flare”) is the arrival time of a photon emitted along the line of sight at  $R_{IS}$  and  $t_{IS}$ , relative to a photon emitted at  $R = 0$  and  $t = 0$ , which is given by

$$t_{fl,onset} = t_{IS} - \frac{R_{IS}}{c} = t_{ej} + \frac{\beta_2(1 - \beta_1)\Delta t_{ej}}{\beta_2 - \beta_1} \cong t_{ej} + \frac{\Delta t_{ej}}{1 - (\gamma_1/\gamma_2)^2} \approx t_{ej} + \frac{\gamma}{\Delta\gamma} \frac{\Delta t_{ej}}{2}. \quad (A2)$$

The exact observed time at which the flare peaks,  $t_{fl}$ , would be somewhat later, typically by about the shell shock crossing time. The latter depends on the details of the shell (width, Lorentz factor and mass density distribution within the shell, etc.) but is generally expected to be of the order of  $t_{fl,onset} - t_{ej}$ . Furthermore, the typical width of the spike in the light curve,  $\Delta t_{fl}$ , is of the order of the angular time (which is typically also of the order of the radial time or shock crossing time), and since  $\Delta R_{IS} \sim R_{IS}$ , we have

$$\Delta t_{fl} \sim \frac{R_{IS}}{c\gamma^2} \approx \frac{\gamma}{\Delta\gamma} \Delta t_{ej} \sim t_{fl} - t_{ej} \sim 2(t_{fl,onset} - t_{ej}). \quad (A3)$$

In order for  $\Delta\gamma$  to be meaningful, we assume that it is larger than the spread in the Lorentz factor within each shell, so that the shells do not spread significantly before  $R_{IS}$ , and their width (in the lab frame) is of order  $c\Delta t_{ej}$ .

The values of the spectral break frequencies depend on the physical conditions within the shocked shells. The isotropic equivalent kinetic luminosity of the outflow is given by  $L_{iso} \approx 4\pi R^2 \gamma^2 \rho' c^3$ , while the total luminosity is  $(1 + \sigma)L_{iso}$ , where  $\sigma = (B')^2 / 4\pi \rho' c^2$  is

the ratio of electromagnetic to kinetic energies of the outflow, and primed quantities are measured in the comoving frame. The relative velocity between the two shells is

$$\beta_{21} = \frac{\beta_2 - \beta_1}{1 - \beta_2\beta_1} \cong \frac{\gamma_2^2 - \gamma_1^2}{\gamma_2^2 + \gamma_1^2} \approx \frac{\Delta\gamma}{\gamma} \ll 1. \quad (\text{A4})$$

Thus, the shocks going into the two colliding shells are Newtonian for  $\Delta\gamma/\gamma \ll 1$ , and the compression ratio is  $\rho'_{\text{ps}}/\rho' \approx 4$ , where the subscript “ps” is for “postshock.” For equal density shells, the relative velocity of the upstream and downstream fluids is  $\beta_{\text{ud}} \approx \beta_{21}/2 \approx \Delta\gamma/2\gamma$ , and the internal energy per unit rest-energy is<sup>8</sup>  $e'_{\text{ps}}/\rho'_{\text{ps}}c^2 \approx \beta_{\text{ud}}^2/2 \approx (\Delta\gamma/\gamma)^2/8$ . Thus, the minimal random Lorentz factor of the power-law distribution of relativistic electrons scales as

$$\gamma_m \propto \epsilon_e \frac{e'_{\text{ps}}}{\rho'_{\text{ps}}} \propto \epsilon_e \left( \frac{\Delta\gamma}{\gamma} \right)^2, \quad (\text{A5})$$

where  $\epsilon_e$  is the fraction of the postshock internal energy that goes into such a population of relativistic electrons. The internal energy in the shocked regions scales as

$$e'_{\text{ps}} \sim \frac{1}{8} \left( \frac{\Delta\gamma}{\gamma} \right)^2 \rho' c^2 \propto \left( \frac{\Delta\gamma}{\gamma} \right)^2 \frac{L_{\text{iso}}}{\gamma^2 R^2} \propto \left( \frac{\Delta\gamma}{\gamma} \right)^4 \frac{L_{\text{iso}}}{\gamma^6 (\Delta t_{\text{ej}})^2}, \quad (\text{A6})$$

where we evaluate the values of the relevant quantities at  $R \approx R_{\text{IS}}$ , using equation (A1).

If the magnetic field holds a constant fraction,  $\epsilon_B$ , of the internal energy behind the shock, as is often assumed for a shock-generated magnetic field, then such an equipartition field<sup>9</sup> would scale as

$$B'_{\text{eq}} \propto (\epsilon_B e'_{\text{ps}})^{1/2} \propto \epsilon_B^{1/2} \left( \frac{\Delta\gamma}{\gamma} \right)^2 L_{\text{iso}}^{1/2} \gamma^{-3} (\Delta t_{\text{ej}})^{-1}. \quad (\text{A7})$$

However, some magnetic field is expected to be advected with the outflow from the central source. At large distances from the source such a field is expected to be primarily in the tangential direction (normal to the radial direction), so that it would be amplified in the shock by the compression ratio,  $B'_{\text{adv,ps}} \approx 4B'_{\text{adv}}$ , where  $(B'_{\text{adv}})^2 = 4\pi\rho'c^2\sigma$ . Thus, for equal mass shells the ratio of the magnetic energy density associated with this field to the internal energy density in the shocked region is  $(B'_{\text{adv,ps}})^2/8\pi e'_{\text{ps}} \approx 64\sigma(\Delta\gamma/\gamma)^{-2}$ , so that the shock compressed advected field would typically exceed an equipartition shock generated field for reasonable values of  $\sigma$ , i.e.,  $\sigma \gtrsim 10^{-3}(\Delta\gamma/\gamma)^2(\epsilon_B/0.1)$ . In this case  $B'_{\text{ps}} \approx B'_{\text{adv,ps}}$ , where

$$B'_{\text{adv,ps}} \approx 8c\sqrt{\pi\rho'\sigma} \propto \sigma^{1/2} \left( \frac{\Delta\gamma}{\gamma} \right) L_{\text{iso}}^{1/2} \gamma^{-3} (\Delta t_{\text{ej}})^{-1}. \quad (\text{A8})$$

The synchrotron frequency of the electrons with the minimal random Lorentz factor,  $\gamma_m$ , scales as

$$\nu_m \approx \gamma \frac{eB'_{\text{ps}}\gamma_m^2}{2\pi m_e c} \propto \begin{cases} \epsilon_B^{1/2} \left( \frac{\Delta\gamma}{\gamma} \right)^6 \epsilon_e^2 L_{\text{iso}}^{1/2} \gamma^{-2} (\Delta t_{\text{ej}})^{-1} & \text{for equipartition,} \\ \sigma^{1/2} \left( \frac{\Delta\gamma}{\gamma} \right)^5 \epsilon_e^2 L_{\text{iso}}^{1/2} \gamma^{-2} (\Delta t_{\text{ej}})^{-1} & \text{for an advected field.} \end{cases} \quad (\text{A9})$$

The random Lorentz factor of electrons that cool on the dynamical time (shell crossing time),  $t' \sim R_{\text{IS}}/\gamma$ , scales as

$$\gamma_c \approx \frac{6\pi m_e c}{\sigma_{\text{T}} (B'_{\text{ps}})^2 (R_{\text{IS}}/\gamma)(1+Y)} \propto \begin{cases} (1+Y)^{-1} \epsilon_B^{-1} \left( \frac{\Delta\gamma}{\gamma} \right)^{-3} L_{\text{iso}}^{-1} \gamma^5 \Delta t_{\text{ej}} & \text{for equipartition,} \\ (1+Y)^{-1} \sigma^{-1} \left( \frac{\Delta\gamma}{\gamma} \right)^{-1} L_{\text{iso}}^{-1} \gamma^5 \Delta t_{\text{ej}} & \text{for an advected field,} \end{cases} \quad (\text{A10})$$

where  $Y$  is the Compton  $y$ -parameter.

The factor of  $(1+Y)$  can be safely dropped from the expression for the advected field, since in this case  $Y \ll 1$  (it is included here for completeness). This can be seen as follows. In general  $Y(1+Y) \approx \beta_{2,\text{sh}}\epsilon_{\text{rad}}\epsilon_e/\epsilon_B$  (see, e.g., Sari & Esin 2001), where  $\beta_{2,\text{sh}}$  is the velocity of the downstream medium relative to the shock front, which in our case is  $\beta_{2,\text{sh}} \sim \beta_{21} \approx \Delta\gamma/\gamma \ll 1$ , and  $\epsilon_{\text{rad}} \sim \min[1, (\nu_m/\nu_c)^{(p-2)/2}]$  is the fraction of the energy in the postshock power-law distribution of relativistic electrons that is radiated away. Here  $\epsilon_B = (B'_{\text{ps}})^2/8\pi e'_{\text{ps}}$ , which

<sup>8</sup> In this case, if the mass of the shells is also the same, the two shocks finish crossing the two shells together, and this is also the fraction  $\epsilon$  of the total energy that is converted into internal energy. As shown below, for a fixed Lorentz factor contrast  $\Delta\gamma/\gamma$ ,  $\epsilon$  is maximal for equal mass shells.

<sup>9</sup> We use the term “equipartition field” for simplicity, even though strictly speaking it holds a constant fraction ( $\epsilon_B^{1/2}$ , generally smaller than unity) of the equipartition value.

for a subequipartition field is  $< 1$ , but for a field advected from the source and compressed by the shock it is (see above)  $\approx 64\sigma(\Delta\gamma/\gamma)^{-2}$ , which is  $\gg 1$  unless the magnetization of the outflow is extremely low,  $\sigma \lesssim 10^{-2}(\Delta\gamma/\gamma)^2$ . Thus,  $Y \sim \epsilon_e \epsilon_{\text{rad}} 10^{-2} \sigma^{-1} (\Delta\gamma/\gamma)^3 \ll 1$ . For a shock-generated field that is a constant fraction of equipartition  $Y$  would also be small unless  $\epsilon_{\text{rad}} \epsilon_e / \epsilon_B \gtrsim \gamma / \Delta\gamma$ .

The cooling break frequency thus scales as

$$\nu_c \approx \gamma \frac{e B'_{\text{ps}} \gamma_c^2}{2\pi m_e c} \propto \begin{cases} (1+Y)^{-2} \epsilon_B^{-3/2} \left(\frac{\Delta\gamma}{\gamma}\right)^{-4} L_{\text{iso}}^{-3/2} \gamma^8 \Delta t_{\text{ej}} & \text{for equipartition,} \\ (1+Y)^{-2} \sigma^{-3/2} \left(\frac{\Delta\gamma}{\gamma}\right)^{-1} L_{\text{iso}}^{-3/2} \gamma^8 \Delta t_{\text{ej}} & \text{for an advected field.} \end{cases} \quad (\text{A11})$$

Finally, we derive the fraction,  $\epsilon$ , of the total energy that is converted into internal energy during the collision between the two shells (in the limit  $\sigma \ll 1$  and  $\Delta\gamma/\gamma \ll 1$ ). Conservation of energy and momentum read

$$\gamma_1 m_1 + \gamma_2 m_2 = \gamma_f M, \quad (\text{A12})$$

$$\gamma_1 \beta_1 m_1 + \gamma_2 \beta_2 m_2 = \gamma_f \beta_f M, \quad (\text{A13})$$

where  $\gamma_f = (1 - \beta_f^2)^{-1/2}$  is the final Lorentz factor and  $M = m_1 + m_2 + E'_{\text{int}}/c^2$ , where  $E'_{\text{int}}$  is the internal energy that was produced in the collision, as measured in the rest frame of the merged shell, while its value in the lab frame is  $E_{\text{int}} = \gamma_f E'_{\text{int}}$ . One obtains  $\beta_f$  from the ratio of the two equations, and for  $\gamma \gg 1$  we have

$$\frac{1}{2\gamma_f^2} \cong 1 - \beta_f = \frac{\gamma_1(1 - \beta_1)m_1 + \gamma_2(1 - \beta_2)m_2}{\gamma_1 m_1 + \gamma_2 m_2} \cong \frac{m_1/\gamma_1 + m_2/\gamma_2}{2(\gamma_1 m_1 + \gamma_2 m_2)}, \quad (\text{A14})$$

and therefore

$$\gamma_f \cong \sqrt{\frac{\gamma_1 m_1 + \gamma_2 m_2}{m_1/\gamma_1 + m_2/\gamma_2}}. \quad (\text{A15})$$

Thus, we have

$$\epsilon = \frac{E_{\text{int}}}{(\gamma_1 m_1 + \gamma_2 m_2) c^2} = 1 - \frac{\gamma_f(m_1 + m_2)}{\gamma_1 m_1 + \gamma_2 m_2} \cong 1 - \left[ 1 + \frac{m_1 m_2}{(m_1 + m_2)^2} \left( \frac{\gamma_2}{\gamma_1} + \frac{\gamma_1}{\gamma_2} - 2 \right) \right]^{-1/2}, \quad (\text{A16})$$

and since for  $\Delta\gamma/\gamma \ll 1$  (in addition to  $\gamma \gg 1$ ),

$$2(\gamma_{21} - 1) \cong \frac{\gamma_2}{\gamma_1} + \frac{\gamma_1}{\gamma_2} - 2 \approx \left( \frac{\Delta\gamma}{\gamma} \right)^2 \ll 1, \quad (\text{A17})$$

then

$$\epsilon \approx \frac{m_1 m_2}{2(m_1 + m_2)^2} \left( \frac{\Delta\gamma}{\gamma} \right)^2 = \frac{x}{2(1+x)^2} \left( \frac{\Delta\gamma}{\gamma} \right)^2, \quad (\text{A18})$$

where  $x = m_2/m_1$  (or alternatively  $m_1/m_2$ ) is the rest-mass ratio of the two shells.

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