CONSTRAINING GAMMA-RAY BURST INITIAL LORENTZ FACTOR WITH THE AFTERGLOW ONSET FEATURE AND DISCOVERY OF A TIGHT $\Gamma_0-E_{\gamma,\text{iso}}$ CORRELATION

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ABSTRACT

The onset of gamma-ray burst (GRB) afterglow is characterized by a smooth bump in the early afterglow light curve as the GRB fireball is decelerated by the circumburst medium. We extensively search for GRBs with such an onset feature in their optical and X-ray light curves from the literature and from the catalog established with the Swift/XRT. Twenty optically selected GRBs and 12 X-ray-selected GRBs are obtained, among which 17 optically selected and 2 X-ray-selected GRBs have redshift measurements. We fit these light curves with a smooth broken power law and measure the width ($w$), rising timescale ($t_r$), and decaying timescale ($t_d$) at full width at half-maximum. Strong mutual correlations among these timescales and with the peak time ($t_p$) are found. The ratio $t_d/t_r$ is almost universal among bursts, but the ratio $t_d/t_p$ varies from 0.3 to $\sim$1. The optical peak luminosity in the $R$ band ($L_{R,\text{p}}$) is anti-correlated with $t_p$ and $w$ in the burst frame, indicating a dimmer and broader bump peaking at a later time. The isotropic prompt gamma-ray energy ($E_{\gamma,\text{iso}}$) is also tightly correlated with $L_{R,\text{p}}$ and $t_p$ in the burst frame. Assuming that the bumps signal the deceleration of the GRB fireballs in a constant density medium, we calculate the initial Lorentz factor ($\Gamma_0$) and the deceleration radius ($R_d$) of the GRBs with redshift measurements. The derived $\Gamma_0$ is typically a few hundreds, and the deceleration radius is $R_{\text{decel}} \sim 2 \times 10^{17}$ cm. More intriguingly, a tight correlation between $\Gamma_0$ and $E_{\gamma,\text{iso}}$ is found, namely $\Gamma_0 \simeq 182(E_{\gamma,\text{iso}}/10^{52}\text{erg})^{0.25}$. This correlation also applies to the small sample of GRBs which show the signature of the afterglow onset in their X-ray afterglow, and to two bursts (GRBs 990123 and 080319B) whose early optical emission is dominated by a reverse shock. The lower limits of $\Gamma_0$ derived from a sample of optical afterglow light curves showing a decaying feature from the beginning of the observation are also generally consistent with such a correlation. The tight lower limits of $\Gamma_0$ of GRBs 080916C and 090902B derived from the opacity constraints with Fermi/LAT observations are also consistent with the correlation at the $2\sigma$ confidence level, but the short GRB 090510 is a clear outlier of this relation. This correlation may give insight to GRB physics and could serve as an indicator of $\Gamma_0$ for long GRBs without early afterglow detections. A comparison of the early X-ray and optical afterglow light curves shows that the early bright X-ray emission is usually dominated by a non-forward-shock component, but occasionally (for one case) the forward shock emission is observable, and an achromatic deceleration feature is observed. The superposition of the internal and external components in X-rays causes the diversity of the observed X-ray light curves.

Key words: gamma-ray burst: general – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

The fireball model is the most popular one for the gamma-ray burst (GRB) phenomenon (Mészáros 2002; Zhang & Mészáros 2004; Piran 2004), in which the observed prompt gamma-ray emission is explained by synchrotron (or inverse Compton) emission from the internal shocks in an erratic, unsteady, relativistic fireball (Mészáros & Rees 1993; Rees & Mészáros 1994) and broadband afterglow emission is attributed to synchrotron emission from the external shock when the fireball is decelerated by a circumburst medium (Mészáros & Rees 1997; Sari et al. 1998). To avoid the “compactness problem” of high-energy non-thermal photons detected from GRBs, the fireball is required to move relativistically toward Earth. After an initial radiation-dominated acceleration phase, the fireball enters a matter-dominated “coasting” phase, keeping an approximate constant Lorentz factor ($\Gamma$) until it sweeps up a considerable amount of mass from the ambient medium at the so-called deceleration radius ($R_d$), after which $\Gamma$ decreases significantly and approaches a self-similar solution characterized by a power-law decay with $R$ and the observer time $t$. The Lorentz factor during the coasting phase is called the initial Lorentz factor ($\Gamma_0$), which is a crucial parameter to understand GRB physics, but is poorly known for most GRBs.

Three methods have been proposed to estimate $\Gamma_0$ of a GRB fireball. The first one is based on the “compactness” argument with the high-energy cutoff of the prompt gamma-ray spectrum (Fenimore et al. 1993; Woods & Loeb 1995; Baring & Harding 1997; Lithwick & Sari 2001). However, this method suffers great uncertainties. Theoretically, the cutoff energy depends on both $\Gamma_0$ and the emission radius $R_e$ (Gupta & Zhang 2008), which is $R_e = \Gamma_0 c \delta t$ in the internal shock model. Such an assumption is not necessarily correct, and the minimum variability timescale $\delta t$ is subject to large uncertainty because the GRB light curves are chaotic without a characteristic timescale. Observationally, so far no clear cutoff feature is observed in the GRB spectrum for most GRBs (Abdo et al. 2009a; Zhang et al. 2010), and a distinct high-energy component in the GeV range, which may come from a different emission region, is observed in a few GRBs, such as 090510 (Abdo et al. 2009b) and GRB 090902B (Abdo et al. 2009c). Therefore, constraints on $\Gamma_0$ with the cutoff energy or the detected highest photon energy may lead...
to erroneous conclusions. The second approach to estimate $\Gamma_0$ is using the blackbody component detected in some GRB spectra (Pe'er et al. 2007). However, observations with Fermi show that no thermal emission component is reliably identified from the broadband spectra for the Fermi GRBs, except for GRB 090902B (Ryde et al. 2010; Zhang et al. 2010). The third, more commonly adopted method is using the early afterglow light curves that show the signal of fireball deceleration. A smooth onset bump peaking at a time when roughly half of the fireball energy is transferred to the medium in the early afterglow light curve is predicted in the fireball model (Sari & Piran 1999; Kobayashi & Zhang 2007). The most relevant case is the thin shell regime, defined when the thickness of the fireball shell satisfies $\Delta < (E/(nmc^2))^{1/3}t_0^{-8/3}$, where $E$ is the kinetic energy of the fireball, $n$ is the circumburst medium density, $m_p$ is the mass of proton, and $c$ is the speed of light (Sari & Piran 1999; Kobayashi 2000). Within this regime, the deceleration time (the peak time at the light curve bump), $t_p \propto \Gamma_0^{-8/3}(E/n)^{1/3}$ (Meszáros & Rees 1993), sensitively depends on the initial Lorentz factor but is rather insensitive to other parameters. The detection of $t_p$ can then be used to infer $\Gamma_0$. In the optical band, early emission may be contaminated by the emission from the reverse shock (Meszáros & Rees 1997; Sari & Piran 1999; Kobayashi 2000; Zhang et al. 2003). However, under certain conditions (either a Poynting flux dominated flow, Zhang & Kobayashi 2005; or a relatively low typical synchrotron frequency in the reverse shock, Jin & Fan 2007), the reverse shock component would not show up in the optical band. In these bursts, a smooth onset bump can be detected, which signals the deceleration feature of the fireball, and hence, can be used to constrain the initial Lorentz factor and the deceleration radius (Sari & Piran 1999; Zhang et al. 2003; Molinari et al. 2007; Xue et al. 2009; Zou et al. 2009).

In this paper, we constrain $\Gamma_0$ with the early GRB afterglows that show the deceleration signature and investigate the possible correlations among deceleration parameters (including $\Gamma_0$) as well as the prompt gamma-ray emission properties. We extensively search for the onset of afterglow signature in the optical and X-ray light curves. Our sample selection criteria are presented in Section 2. The temporal characteristics and their correlations are presented in Section 3. The relation between the prompt gamma-ray properties and the deceleration properties is investigated in Section 4. In particular, we constrain $\Gamma_0$ and the deceleration radius of the fireball for the $z$-known sample, and discover a tight correlation between $\Gamma_0$ and $E_{\gamma,iso}$. Discussion and conclusions are presented in Sections 5 and 6, respectively. A concordance cosmology with parameters $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.30$, and $\Omega_{\Lambda} = 0.70$ is adopted. The notation $Q_*$ denotes $Q/10^9$ in ergs units throughout the paper.

2. SAMPLE SELECTION AND LIGHT CURVE FITTING

We extensively search for the smooth “bump” feature at the onset of the GRB afterglows. Two criteria are employed. (1) Since flares and some X-ray plateau features followed by steep drop near the end (internal plateaus; Liang et al. 2007; Troja et al. 2007; Lyons et al. 2010) are related to internal emission of late central engine activities (Zhang et al. 2006), our first criterion is to search for smooth bumps without the superposition of significant flare-like components. (2) In the optical band, early emission is sometimes contaminated by the emission from the reverse shock or internal shocks, which are characterized by a decay slope of $-2$ or steeper. Our second criterion is therefore to require the decay slope after the bump feature to be shallower than $-2$. Through the literature search, we obtain 20 optically selected GRBs that show the afterglow onset feature. We also go through the Swift/XRT light curve archive that has been processed by our group in the past (from 2005 January to 2009 September), and identify 12 X-ray selected sample with afterglow onset signature. The observational results of these bursts are summarized in Tables 1 and 2. The details of XRT data reduction have been presented in a series of papers published by our group (Zhang et al. 2007, Paper I; Liang et al. 2007, 2008, 2009; Papers II, III, IV). The prompt gamma-ray properties of the bursts are taken from the published papers or GCN reports.

The afterglow light curves of the optically selected and X-ray-selected samples are presented in Figures 1 and 2, respectively. The early X-ray afterglow light curves for the optically selected sample and the optical afterglow light curves for the X-ray selected sample are also presented, if they are available. In the X-ray selected sample, only a few cases have simultaneous optical observations. Nineteen out of 20 GRBs in the optically selected sample have simultaneous X-ray observations. We find only one case, GRB 080319C, that tentatively shows an achromatic onset bump in both the optical and X-ray bands, although the X-ray peak has a large error. This suggests that the external shock emission indeed contributes to both the optical and the X-ray band for this burst. For most optically selected GRBs, on the other hand, either the early X-ray light curves show erratic X-ray flares or internal plateaus that are believed to be powered by the GRB central engine, or the X-ray observations started only after the optical bump peak. Inspecting the two samples shown in Figures 1 and 2, we find that the onset bumps in the optically selected sample are usually smoother than those observed in the X-ray-selected sample. We fit the light curves with an empirical model proposed by Kocevski & Liang (2001),

$$F(t) = F_p \left(\frac{t + t_0}{t_p + t_0}\right)^{t + t_0} \left[\frac{d}{r + d} + \frac{r}{r + d} \left(\frac{t + t_0}{t_p + t_0}\right)^{r+1}\right]^\frac{-3t_0}{d},$$

where $F_p$ is the maximum flux at $t_p$, $t_0$ is a reference time, and $r$ and $d$ are the rising and decaying power-law indices, respectively. An IDL routine named mpfitfun.pro is employed for our fitting. This routine performs Levenberg–Marquardt least-square fit to the data for a given model. It optimizes the model parameters so that the sum of the squares of the deviations between the data and the model becomes minimal. The time interval and the fitting curve for each GRB are shown in Figures 1 and 2, and the fitting parameters are summarized in Tables 1 and 2.\footnote{The reduced $\chi^2$ of our fits for some optical light curves are large. This is due to the fluctuations in the light curves and small observational errors in the optical data.} Note that the light curves of some GRBs, such as 050820A, 060607A, 070411, 071031, and 080330, show significant energy injection or re-brightening features after the deceleration bump. We make our fits only around the bump. We take the full width at half-maximum (FWHM) of a fitting curve as a characteristic width ($\sigma$) of the bump and measure the rising and decaying timescales ($t_r$ and $t_d$) at FWHM. We also derive the ratios of $t_r/t_d$ and $t_d/t_d$. The results are reported in Tables 1 and 2.

Seventeen out of 20 GRBs in the optically selected sample and 2 out of 12 GRBs in the X-ray-selected sample have
redshift measurements. In the following, we mostly only use the z-known optically selected sample, but use the z-known X-ray-selected sample to confirm the findings. Most of these GRBs are detected with Swift/BAT. It is well known that the GRB spectrum is well fit with the Band function (Band et al. 1993). Due to the narrowness of the BAT energy band (15–150 keV), the true spectral parameters and the bolometric energy of the prompt gamma-rays ($E_{\gamma,\text{iso}}$, defined in the 1–10^4 keV band in the rest frame of the burst) of these GRBs are poorly constrained. The spectra observed with BAT are usually adequately fit with a single power law. Seven out of the 17 z-known GRBs in the optically selected sample, including GRBs 050820A, 060418, 060904B, 061007, 070318, 080319C, and 080810, were simultaneously observed with Konus/Wind, Suzaku, or Fermi/GBM. Their spectral parameters and $E_{\gamma,\text{iso}}$ were derived from the joint spectral fits of the observations by these instruments (Krimm et al. 2009; Centeno et al. 2006; Page et al. 2009). For other GRBs, the spectral parameters and $E_{\gamma,\text{iso}}$ in the 1–10^4 keV band are taken from Butler et al. (2007, 2010), in which a complete and extensive spectral analysis for the Swift GRBs is presented using a unified methodology, although the spectral parameters and $E_{\gamma,\text{iso}}$ have great uncertainties. The derived $E_{\gamma,\text{iso}}$ is reported in Table 3.

We collect the optical spectral index ($\beta_O$) and host galaxy extinction ($A_V$) of each GRB from the literature. They are reported in Table 3. The spectral index $\beta_O$ is taken as 0.75 if it is not available. Most optically selected light curves in our sample are measured in the $R$ band. We therefore correct the observed light curves in the other bands to the $R$ band using the spectral index. Since the $\beta_O$ value of GRB 060605 is unreasonably...
Figure 1. Light curves of the optically selected sample (dots). Lines are the best fits with a smooth broken power law to the optical data in a selected interval marked as the red solid segment. Blue dashed lines just extend the fitting curves to a broader time regime. The simultaneous X-ray data observed with Swift/XRT (crosses with error bands) are also presented.

(A color version of this figure is available in the online journal.)
large, we take its $\beta_O$ as 0.75. All data have been corrected for extinction in the Milky Way and the GRB host galaxy assuming an LMC extinction curve. Finally, we derive the rest-frame R-band flux using the $k$-correction $F_R = F_{R,\text{obs}}(1 + z)^{\beta_O - 1}$. We then calculate the rest-frame R-band peak luminosity ($L_{R,p}$) based on the burst redshift, and calculate the isotropic rest-frame R-band energy ($E_{R,\text{iso}}$) by integrating the luminosity from 10 to $10^5$ s after the GRB trigger. We do not consider the error on $E_{R,\text{iso}}$ since they are calculated using integration of the fitted light curves. The results are also reported in Table 3.

6 GRB 060605 is at $z = 3.773$. The spectral index is affected by Ly$\alpha$ and Lyman-limit blanketing.

3. CHARACTERISTICS OF THE ONSET BUMP AND THEIR CORRELATIONS

The following statistics applies to the optically selected sample. The distributions of $r$, $d$, $t_p$,$t_d$, $F_p$, $w$, $t_r$/$t_p$, and $t_r$/$t_d$ are shown in Figure 3. It is found that the rising index $r$ of most bursts is in the range of 1–2, with three exceptional cases, i.e., GRBs 080330 ($r = 0.34 \pm 0.03$), 060607A ($r = 4.15 \pm 0.22$), and 050820A ($4.45 \pm 0.76$). The optical light curve of the afterglow of GRB 080330 rises slowly, keeping almost constant in 300–1000 s post-GRB trigger. This feature is similar to that observed in GRB 060614. For GRBs 060607A and 050820A, their optical light curves rapidly rise and decay normally after the peak as predicted by the forward shock models. Considering the first data point of GRB 061007, the rising index is also very steep ($r \sim 4.90$), but our fitting model cannot yield
Figure 2. Same as Figure 1, but for the X-ray-selected sample. The optical data points are presented for GRBs 080307 and 080319C. (A color version of this figure is available in the online journal.)
Table 3
Derived Intrinsic Properties of the Bursts with Redshift Measure in the Optically Selected Sample

| GRB | $z_{rel}$ | $E_{\gamma,iso}$ | $t_{p,2}$ | $t_{p,3}$ | $A_R$ | $L_{R,P}$ | $E_{R,iso}$ | $\Gamma_0$ | $R_3$ |
|-----|-----------|-----------------|-----------|-----------|-------|------------|-------------|----------|-------|
| 050730 | 3.97(1) | 9.8±3 | 120.99 ± 27.76 | 0.82±0.04 | 0.100 ± 0.015 | 4.33 ± 0.58 | 120 | 289±4 | 2.26±0.02 |
| 050820A | 2.615(2) | 97±31 | 108.17 ± 4.62 | 0.96±0.03 | 0.065 ± 0.008 | 11.13 ± 0.78 | 162 | 332±21 | 2.69±0.37 |
| 060418 | 1.49(3) | $10^{\gamma}$ | 60.73 ± 0.82 | 0.65±0.06 | ~0.1 | 12.57 ± 0.77 | 111 | 379±10 | 1.96±0.34 |
| 060605 | 3.8(4) | $2.5^{+3.1}_{-0.6}$ | 83.14 ± 2.70 | 4.64±0.58 | ... | 8.82 ± 0.82 | 185 | 283±44 | 1.50±0.47 |
| 060607A | 3.082(5) | $9^{+7}_{-2}$ | 42.89 ± 0.62 | 0.56±0.05 | 0.41±0.14 | 11.42 ± 0.83 | 65 | 426±41 | 1.75±0.34 |
| 060904B | 0.703(6) | 0.72±0.43 | 271.91 ± 33.75 | 0.75±0.1 | 0.44 ± 0.05 | 0.09 ± 0.01 | 6 | 155±14 | 1.48±0.32 |
| 061007 | 1.262(7) | 104.65±6.94 | 34.62 ± 0.18 | 0.99±0.05 | 0.66 ± 0.02 | 155.75 ± 1.21 | 738 | 627±3 | 3.06±0.05 |
| 070318 | 0.84(6) | $1.45^{+0.38}_{-0.38}$ | 162.95 ± 15.26 | 0.75±0.1 | ... | 0.39 ± 0.04 | 17 | 206±10 | 1.54±0.21 |
| 070411 | 2.954(9) | $10^{\gamma}$ | 113.83 ± 1.27 | 0.75±0.1 | ... | 1.97 ± 0.27 | 59 | 299±8 | 2.29±0.12 |
| 070419A | 0.97(10) | $2.46^{+0.23}_{-0.05}$ | 297.98 ± 10.62 | 0.82±0.16 | 0.37 ± 0.19 | 0.02 ± 0.01 | 1 | 131±16 | 1.15±0.08 |
| 071010A | 0.98(11) | $1.30^{+0.24}_{-0.01}$ | 185.95 ± 12.31 | 0.76±0.26 | 0.62 ± 0.15 | 0.03 ± 0.00 | 7 | 145±34 | 0.87±0.07 |
| 071031 | 2.692(12) | $3.9^{+4.1}_{-1.6}$ | 275.88 ± 0.42 | 0.78±0.03 | 0.30 ± 0.05 | 24 | 191±25 | 2.26±0.99 |
| 080319C | 1.95(13) | $22.55^{+3.35}_{-3.35}$ | 117.38 ± 3.22 | 0.75±0.1 | 0.67 ± 0.06 | 0.05 ± 0.02 | 10 | 327±7 | 2.83±0.14 |
| 080330 | 1.51(14) | $0.41^{+0.10}_{-0.06}$ | 247.77 ± 6.79 | 0.61±0.03 | ... | 0.15 ± 0.15 | 1 | 150±43 | 1.25±0.72 |
| 080710 | 0.845(15) | $0.8^{+0.8}_{-0.4}$ | 1192.91 ± 2.24 | 1.0±0.02 | ... | 0.11 ± 0.01 | 32 | 90±3 | 2.19±0.55 |
| 080810 | 3.35(16) | $30^{+20}_{-20}$ | 27.02 ± 0.26 | 0.51±0.29 | 0.22 | 52.55 ± 17.02 | 306 | 588±49 | 2.10±0.35 |
| 081203A | 2.1(17) | $17^{+11}_{-11}$ | 118.09 ± 0.46 | 0.9±0.01 | 0.01 | 0.08 | 29.91 ± 0.36 | 557 | 315±30 | 2.64±0.05 |

Notes.

* GRBs 050820A, 060418, 060904B, 061007, 070318, 080319C, and 080810 were simultaneously observed with BAT and Konus/Wind, or Suzaku, or Fermi/GBM. Their spectral parameters and the $E_{\gamma,iso}$ (in units of erg) in 1–10$^8$ keV band in the burst frame were taken from Krimm et al. (2009), Cenko et al. (2006), and Page et al. (2009). The spectral parameters and the $E_{\gamma,iso}$ of other GRBs are taken from Butler et al. (2007, 2010).

* In units of seconds.

* The observed optical spectral index $A_R$ of the GRB host galaxy. The references of the optical data are the same as that in Table 1.

* The $R$-band peak luminosity (in units of 10$^{47}$ erg cm$^{-2}$ s$^{-1}$) and isotropic energy (in units of 10$^{48}$ erg) in 10$^{-10}$ s post the GRB trigger.

* In units of 10$^{17}$ cm.

References.

(1) Rol et al. 2005; (2) Ledoux et al. 2005; (3) Prochaska et al. 2006; (4) Ferrero et al. 2009; (5) Ledoux et al. 2006; (6) Fugazza et al. 2006; (7) Jakobsson et al. 2007b; (8) Chen et al. 2007; (9) Jakobsson et al. 2007a; (10) Cenko et al. 2007b; (11) Prochaska et al. 2007; (12) Ledoux et al. 2007; (13) Wiersema et al. 2008; (14) Cucchiara 2008; (15) Perley et al. 2008a; (16) Prochaska et al. 2008; (17) Landsman et al. 2008.

Table 4
Spearman Pair-correlation Coefficients of the Characteristics of the Optically Selected Samples

| $L_{R,P}$ | $t_p$ | $r$ | $d$ | $t_d$ | $t_{p,3}$ | $t_d/t_p$ | $w$ |
|-----------|------|----|----|------|--------|---------|-----|
| −0.90     | X X | −0.89 | −0.88 | X X | −0.88 |
| $t'_p$    | X X | 0.95 | 0.93 | X X | 0.94 |
| $r$       | X X | 0.90 | 0.90 | X   | 0.90 |
| $d$       | X   | X X | X   | X   | X     |
| $t'_d$    | 0.98 | X   | 0.98 | X   | 0.98 |
| $t_d/t_d$ | X   | X   | X   | X   | 1      |
| $t_{p,3}$ | $t_{p,3}$ | $t_p$ | $w$ |

$log t_d = (−0.54 ± 0.22) + (1.11 ± 0.08) \log t_p$, \hfill (4)

$log w = (0.05 ± 0.27) + (1.16 ± 0.10) \log t_p$, \hfill (5)

$log w = (0.61 ± 0.11) + (1.05 ± 0.05) \log t_r$, \hfill (6)

$log w = (0.15 ± 0.02) + (0.98 ± 0.01) \log t_d$. \hfill (7)

These tight correlations suggest that the structures of the bumps among these bursts are similar, indicating a universal physical origin. An interesting characteristic is that a wider bump tends to peak at a later time. This is consistent with the expectation of the external shock model, since a later deceleration time corresponds to a smaller Lorentz factor, and hence, a longer
angular spreading time $R/\Gamma^2c$. No correlation between the decay index $d$ and other parameters is found.

This is also consistent with the expectations from the fireball model, where the decay slope is dictated by the density profile and the electron spectral index $p$ but is independent on the details of the afterglow onset. On the other hand, the rising index $r$ is tightly anti-correlated with both the ratio $t_r/t_d$ and $t_r/t_p$, although it is not correlated with $t_r$ and $t_d$. These correlations read

$$\log r = (-0.21 \pm 0.06) - (1.68 \pm 0.19) \log t_r/t_d, \quad (8)$$

$$\log r = (-0.15 \pm 0.02) - (0.48 \pm 0.05) \log t_r/t_d. \quad (9)$$

In addition, both $w$ and $t_p$ in the burst frame ($w_z$ and $t_p,z$) are anti-correlated with $L_{R,p}$, i.e.,

$$\log L_{R,p,47} = (5.61 \pm 0.83) - (2.49 \pm 0.39) \log t_p,z, \quad (10)$$

$$\log L_{R,p,47} = (5.43 \pm 0.84) - (2.00 \pm 0.32) \log w_z. \quad (11)$$

These results suggest that a dimmer bump tends to peak at a later time with a longer duration. This is again consistent with the expectation of the external shock model, since a later deceleration time corresponds to a smaller Lorentz factor, and hence, a weaker forward shock with fainter emission.
4. INITIAL LORENTZ FACTOR CONSTRAINTS AND THE \( \gamma_0 - E_{\gamma, \text{iso}} \) CORRELATION

The observational properties of the early optical bumps seem to be due to the onset of the external shock afterglow in the thin shell regime. To further test this hypothesis, we show the correlations of \( L_{R, p} \), \( E_{R, \text{iso}} \), and \( t_{p, z} \) with \( E_{\gamma, \text{iso}} \) in Figure 5, and report their linear coefficients and chance probabilities in Table 5. It is found that they are correlated, i.e.,

\[
\begin{align*}
\log L_{R, 0.47} &= (0.83 \pm 0.15) + (1.40 \pm 0.08) \log E_{\gamma, \text{iso}, 52} \tag{12} \\
\log E_{R, \text{iso}, 48} &= (1.30 \pm 0.14) + (0.76 \pm 0.14) \log E_{\gamma, \text{iso}, 52} \tag{13} \\
\log t_{p, z} &= (2.35 \pm 0.09) - (0.40 \pm 0.07) \log E_{\gamma, \text{iso}, 52} \tag{14}
\end{align*}
\]

These correlations indicate that a GRB with a larger \( E_{\gamma, \text{iso}} \) tends to have a brighter optical afterglow peaking at an earlier time, being consistent with the afterglow onset theory.

The shape of the light curve agrees with the thin shell case (cf. the thick shell case; see Kobayashi et al. 1999; Kobayashi & Zhang 2007). We therefore apply the standard afterglow model in a constant density medium (Sari & Piran 1999) to derive the initial Lorentz factor,

\[
\Gamma_0 = 2 \left[ \frac{3E_{\gamma, \text{iso}}}{32\pi nm_pc^5 \eta t_{p, z}^3} \right]^{1/8} \simeq 193(n\eta)^{-1/8} \times \left( \frac{E_{\gamma, \text{iso}, 52}}{t_{p, z}^{1/2}} \right)^{1/8},
\tag{15}
\]

Table 5

| \( r_{p, z} - E_{\gamma, \text{iso}} \) | \( L_{R, p} - E_{\gamma, \text{iso}} \) | \( E_{R, \text{iso}} - E_{\gamma, \text{iso}} \) | \( L_{R, p} - \Gamma_0 \) | \( t_{p, z} - \Gamma_0 \) | \( E_{\gamma, \text{iso}} - \Gamma_0 \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( r \)         | \( -0.69 \)     | \( 0.87 \)      | \( 0.82 \)      | \( 0.93 \)      | \( 0.89 \)      | \( 0.94 \)      |
| \( p \)         | \( 0.002 \)     | \( <10^{-4} \)  | \( <10^{-4} \)  | \( <10^{-4} \)  | \( <10^{-4} \)  | \( <10^{-4} \)  |
and the deceleration radius

$$R_d = 2c t_p \Gamma_p^2/(1 + z) = 2.25 \times 10^{16} \, \text{cm} \, \Gamma_d^2 t_p, \quad (16)$$

where $n$ is the ambient density and $\eta = E_{\gamma, \text{iso}}/E_{K, \text{iso}}$ is the ratio between the isotropic gamma-ray energy and the isotropic blastwave kinetic energy. The results are rather insensitive to $n$ and $\eta$. We take $n = 1 \, \text{cm}^{-3}$ and $\eta = 0.2$ in the following analysis.

With the data reported in Table 3, we calculate $\Gamma_0$ and $R_d$ for the GRBs in the optically selected sample. The results are also reported in Table 3. The distributions of the derived $\Gamma_0$ and $R_d$ are displayed in Figure 6. The derived $\Gamma_0$ is typically a few hundreds, and the typical deceleration radius is $R_d = 2 \times 10^{17}$. From Equation (15), we find that $\Gamma_0$ depends on both $t_p$ and $E_{\gamma, \text{iso}}$. As $t_p$ is tightly correlated with $E_{\text{iso}}$, one expects tight relations between $\Gamma_0$ and $E_{\gamma, \text{iso}}$ and between $\Gamma_0$ and $t_p$. We show the two correlations in Figure 7. The best fits give

$$\log \Gamma_0 = (3.59 \pm 0.11) - (0.59 \pm 0.05) \log t_p, \quad (17)$$

with the correlation coefficient $\kappa = -0.94$ (chance probability $p < 10^{-4}$) and

$$\log \Gamma_0 = (2.26 \pm 0.03) + (0.25 \pm 0.03) \log E_{\gamma, \text{iso}}, \quad (18)$$

with correlation coefficient $\kappa = 0.89$ (chance probability $< 10^{-4}$). These tight correlations suggest that $t_p$ and $E_{\gamma, \text{iso}}$ are good indicators of $\Gamma_0$ (hence $R_d$). In particular, the latter correlation can be translated to

$$\Gamma_0 \simeq 182 E_{\gamma, \text{iso}}^{0.25 \pm 0.03}, \quad (19)$$

which can be very useful to understand GRB physics (see below).

5. DISCUSSION

5.1. Possible Selection Effects and Intrinsic Scatter of the $\Gamma_0$–$E_{\gamma, \text{iso}}$ Correlation

The $\Gamma_0$–$E_{\gamma, \text{iso}}$ relation is derived from the optically selected sample. In the X-ray-selected sample only two cases have redshift measurements. One case (GRB 080319C) shows an achromatic afterglow onset feature. The derived $E_{\gamma, \text{iso}}$ and $\Gamma_0$ for these two GRBs are reported in Table 6. They are also consistent with the $\Gamma_0$–$E_{\gamma, \text{iso}}$ correlation, as shown in Figure 8. The calculation of $\Gamma_0$ is sensitive to $t_p (\Gamma \propto t_p^{-3/8})$. Therefore, those GRBs that have very early optical afterglow observations but do not show a clear onset feature are important to check the validity of the $\Gamma_0$–$E_{\gamma, \text{iso}}$ correlation. Inspecting the early optical afterglow light curves of GRBs, one finds that the early light curve behavior is rather diverse (e.g., Liang & Zhang 2006; Kann et al. 2010; Panaitescu & Vestrand 2008; Oates et al. 2009). Besides those that are dominated by the onset feature of the forward shock emission (as listed in Table 1), two more types of light curves are relevant to the $\Gamma_0$ constraints discussed in this paper. The first type includes those light curves that show a steeper (a decay slope $\sim 2$ or steeper) decay slope that is consistent with a reverse shock origin (Mészáros & Rees 1997; Sari & Piran 1999; Kobayashi 2000; Zhang et al. 2003). Theoretically, both the forward and the reverse shock emission start to drop after the reverse shock crosses the ejecta shell. So the reverse shock peak time (e.g., that observed in GRB 990123) also corresponds to the deceleration time within this interpretation. The second type of light curves includes those with a simple power-law decay from the very first observation,
and the decay slope is consistent with the standard forward shock model. It is likely that the deceleration time is before the first observational epoch, so that the first data point can place a lower limit to $\Gamma_0$. The same logic applies to those light curves that show an early reverse shock contribution but the peak was missed (e.g., GRB 080319B; Racusin et al. 2008). These cases are illustrated in Figure 9. Their $E_{\gamma,\text{iso}}$ in the 1–10$^4$ keV band in the burst frame, $t_{\text{p},z}$, and $\Gamma_0$ or their limits are reported in Table 6. The derivations of $E_{\gamma,\text{iso}}$ follow the same procedure outlined before. We can see that some $t_{\text{p}}$ or limits are much earlier than those reported in our optically selected sample. On the other hand, some of them (e.g., GRB 990123 and GRB 080319B) also have a much higher $E_{\gamma,\text{iso}}$. We show these GRBs in the $\Gamma_0$–$E_{\gamma,\text{iso}}$ plane in Figure 8 in comparison with the optically selected sample. They are systematically above the best-fit line of the $\Gamma_0$–$E_{\gamma,\text{iso}}$ relation. The scatter of the relation can be measured with the deviation of the ratio $\Gamma_0/E_{\gamma,\text{iso}}^{0.25}$. With the data in Table 1, we get the 1σ deviation of the ratio as 0.11. We show the 2σ region of the relation in Figure 8. It is found that most of the GRBs with a lower limit of $\Gamma_0$ are enclosed within the 2σ region, except for GRB 051111, which is slightly above the region. This means that they may be consistent with the correlation if the peak time is not significantly earlier than the first observation time. Two special events are worth mentioning separately. GRB 990123 is the most intense event among the bursts in our sample. A reverse shock emission peak of this event was detected at $t_{\text{p},z} = 18$ s (Akerlof et al. 1999). It is convincingly shown that this event follows the $\Gamma_0$–$E_{\gamma,\text{iso}}$ correlation well. GRB 080319B is the optically brightest GRB detected so far. Both prompt and afterglow light curves of this
Table 6
Intrinsic Properties and the Derived Initial Lorentz Factors for the GRBs with Detection of X-ray Onset Bump, Optical Forward Shock Peak Time (or Limit), or Tight Limit on Onset Peak Time of the Forward Shock Emission

| GRB     | $z_{\text{ref}}$ | $E_{\gamma,\text{iso}}$ (erg) | $t_{p,x}$ (s) | $\Gamma_0$ | Ref |
|---------|------------------|-------------------------------|--------------|------------|-----|
| X-ray   |                  |                               |              |            |     |
| 070208  | 1.165(1)         | 0.28$^{+0.22}_{-0.08}$       | 447.16 ± 206.54 | 115$^{+23}_{-20}$ | (2) |
| 080319C | 1.95(3)          | 22.55 ± 3.35                 | 146.71 ± 49.73 | 301 ± 39   | (4) |
| Optical |                  |                               |              |            |     |
| 990123  | 1.60(5)          | 436.52 ± 60.31               | ~18          | ~0.066     | (6), (7) |
| 021211  | 1.006(8)         | 11.2 ± 0.08                  | <65          | >282 (6), (9) |
| 050319  | 3.24(10)         | 4.6 ± 0.6                    | <64          | >337 (2), (11) |
| 050525A | 0.606(12)        | 9.54 ± 0.52                  | <58          | >384 (13), (14) |
| 050922C | 2.198(15)        | 5.06 ± 0.55                  | ~42          | ~401 (16), (17) |
| 051111  | 1.55(18)         | 13.14 ± 3.29                 | <60          | >395 (4), (19) |
| 060210  | 3.91(20)         | 41.5 ± 5.7                   | ~97          | ~381 (4), (21) |
| 060908  | 2.43(22)         | 10.70 ± 5.94                 | <38          | >455 (4), (23) |
| 060912  | 0.937(24)        | 1.65 ± 0.24                  | <59          | >307 (25), (23) |
| 061021  | 0.77(26)         | 2.76 ± 0.66                  | <45          | >363 (27), (23) |
| 071003  | 1.6043$^{+55}_{-28}$ | 68.4 ± 10.4                 | <61          | >483 (29), (30) |
| 071010B | 0.9473(31)       | 2.55 ± 0.41                  | <67          | >390 (32), (33) |
| 071112C | 0.8223(34)       | 1.79 ± 0.26                  | <111         | >244 (35), (36) |
| 080319B | 0.937(37)        | 141.00 ± 5.92                | <76          | >486 (38), (39) |

References. (1) Cucchiara et al. 2007; (2) Butler et al. 2007; (3) Wiersema et al. 2008; (4) Krimm et al. 2009; (5) Kulkarni et al. 1999; (6) Liang & Zhang 2005; (7) Galama et al. 1999; (8) Veeswijk et al. 2006; (9) Li et al. 2003; (10) Fynbo et al. 2005; (11) Mason et al. 2006; (12) Foley et al. 2005; (13) Ghirlanda et al. 2008; (14) Blustin et al. 2006; (15) D’Elia et al. 2008; (16) Liang et al. 2008; (17) de Pasquale et al. 2009; (18) Hill et al. 2005; (19) Yost et al. 2007; (20) Cucchiara et al. 2006; (21) Curran et al. 2007; (22) Roll et al. 2006; (23) Oates et al. 2009; (24) Jakobsson et al. 2007a; (25) Golenetskii et al. 2006a; (26) Thöne et al. 2006; (27) Golenetskii et al. 2006b; (28) Perley et al. 2006; (29) Golenetskii et al. 2007a; (30) Perley et al. 2008b; (31) Cenko et al. 2007a; (32) Golenetskii et al. 2008b; (33) Wang et al. 2008; (34) Jakobsson et al. 2008; (35) Krimm et al. 2007; (36) Huang et al. 2009; (37) Racusin et al. 2008; (38) Golenetskii et al. 2008; (39) Bloom et al. 2009.

GRBs are well sampled. A clear steep decay segment following the prompt optical emission phase was detected, which may be powered by the reverse shock (Racusin et al. 2008). The $t_p$ of this segment is likely buried underneath the prompt optical emission, which poses a lower limit on $\Gamma_0$. This limit is also within the 2σ region of the correlation.

It is found that energetic bursts tend to have more luminous afterglows, albeit with a large scatter (e.g., Gehrels et al. 2008; Kann et al. 2010). As shown in Tables 1 and 6, the early peaks are less than hundreds of seconds post GRB trigger. Most early optical observations are carried out by space-based or ground-based, low-sensitivity, robotic telescopes, which bias against detections of early peaks (i.e., large $\Gamma_0$) in low $E_{\gamma,\text{iso}}$ GRBs. This selection effect, if any, may introduce a larger scatter at the low-$E_{\gamma,\text{iso}}$ end of the $\Gamma_0$−$E_{\gamma,\text{iso}}$ relation. The optical observations for typical X-ray flashes (e.g., GRB 020903) and sub-energetic events (e.g., 980425, 031203, and 060218) were not early enough to place an interesting constraint on this issue.

In our analysis, an interstellar medium model with $n = 1$ cm$^{-3}$ and $\eta = 0.2$ was adopted. The dependence of $\Gamma_0$ on $n$ and $\eta$, i.e., $\Gamma_0 \propto (n\eta)^{-1/8}$, is weak. Nonetheless, the variations of $\eta$ and $n$ would also contribute to the dispersion of the $\Gamma_0$−$E_{\gamma,\text{iso}}$ correlation.

5.2. Comparison of Our $\Gamma_0$ Measurements with Those Derived from Fermi Observations

Using a sample of GRBs that show the afterglow onset feature in the early optical/X-ray afterglow light curves, we manage to constrain $\Gamma_0$ for a good sample of GRBs which can be used to perform a statistical study of $\Gamma_0$ for the first time. Using a different method (the opacity constraint), the Fermi team recently sets the lower limits of $\Gamma_0$ for a number of bright GRBs, e.g., $\Gamma_0,\text{min} \sim 800$ for GRB 080916C (Abdo et al. 2009a), $\Gamma_0,\text{min} \sim 1200$ for GRB 090510 (Abdo et al. 2009b), and $\Gamma_0,\text{min} \sim 1000$ for GRB 090902B (Abdo et al. 2009c). These lower limits are also shown in Figure 8. For GRB 080916C, one has $E_{\gamma,\text{iso}} \sim 8.8 \times 10^{54}$ erg (Abdo et al. 2009a), which corresponds to $\Gamma_0 \sim 990_{−121}^{+654}$ (error in 1σ hereafter) according to our $\Gamma_0$−$E_{\gamma,\text{iso}}$ relation and its 1σ dispersion (Equation 19). For GRB 090902B, one has $E_{\gamma,\text{iso}} \sim 3.63 \times 10^{54}$ erg (Abdo et al. 2009c), corresponding to $\Gamma_0 \sim 110$ for this GRB by the Fermi team is based the maximum photon energy of the non-thermal component, but not that of the MeV component.

We should note that, however, GRB 090902B clearly shows a distinct non-thermal component extending to high energy which clearly has a different origin from the MeV component (and very likely from different emission regions; Pe’er et al. 2010). The derived lower limit on $\Gamma_0$ for this burst by the Fermi team is based the maximum photon energy of the non-thermal component, but not that of the MeV component.
5.3. Implications for the $\Gamma_0-E_{\gamma,\text{iso}}$ Correlation

The $\Gamma_0-E_{\gamma,\text{iso}}$ relation is very useful to pin down the prompt emission physics of GRBs. One interesting observational correlation is the Amati relation, i.e., $E_p \propto E_{\gamma,\text{iso}}^\kappa$ (or $E_p \propto L_{\gamma,\text{iso}}^\kappa$, with $\kappa \sim (0.4-0.5)$, both as a bulk correlation among bursts and an internal correlation within a burst (Amati et al. 2002; Wei & Gao 2003; Liang et al. 2004; Yonetoku et al. 2004; Lu & Liang 2010). However, all the prompt GRB emission models predict $E_p$ as a function of both $E_{\gamma,\text{iso}}$ (or $L_{\gamma,\text{iso}}$) and $\Gamma_0$ (e.g., Table 1 of Zhang & Mészáros 2002a). There is no straightforward theory that predicts the relationship between $\Gamma_0$ and $E_{\gamma,\text{iso}}$ (or $L_{\gamma,\text{iso}}$). As a result, any theoretical model can be argued to interpret the Amati relation, given a designed $\Gamma_0-E_{\gamma,\text{iso}}$ correlation. The $\Gamma_0-E_{\gamma,\text{iso}}$ correlation discovered here therefore poses great constraints on many prompt emission models. For example, the internal shock synchrotron model predicts $E_p \propto L^{1/2} \Gamma_0^{-2}$ (Zhang & Mészáros 2002). The Amati relation essentially requires that $\Gamma_0 \propto L$. The $\Gamma_0 \propto E_{\gamma,\text{iso}}^{0.25}$ relation, combined with the trivial proportionality $L \propto E_{\gamma,\text{iso}}$ (a non-correlation between GRB duration and luminosity), would lead to $E_p \propto E_{\gamma,\text{iso}}^{1/2} E_{\gamma,\text{iso}}^{-0.54} \propto E_{\gamma,\text{iso}}^{0.54}$, which means that $E_p$ is essentially constant for different $E_{\gamma,\text{iso}}$ values. This is in contradiction with the Amati relation, which can be regarded as another argument against the internal shock synchrotron emission model of GRB prompt emission (see also Kumar & McMahon 2008; Zhang & Pe'er 2009).

Another possibility to interpret a smooth bump feature in the early afterglow phase may be the light-of-sight effect (Paniaietscu & Vestrand 2008; Guidorzi et al. 2009; Margutti et al. 2010). This requires that the GRB jet is uniform with a sharp edge, and the light of sight is outside the jet cone. The afterglow peak then corresponds to the epoch when the $1/\Gamma$ cone enters the line of sight, and the measured $\Gamma$ is not the initial Lorentz factor of the ejecta, but is the Lorentz factor defined by $(\theta_v - \theta_j) = 1/\Gamma$, where $\theta_v$ and $\theta_j$ are the viewing angle and the jet opening angle, respectively. The data in our sample may disfavor this scenario. It predicts that rising index of the light curve is very steep, say, $r \sim (3-4)$ (Panaitescu & Vestrand 2008). This is inconsistent with the $r$ values derived for the bursts in our sample (except for GRBs 050820A and 060607A). The second issue is related to statistics. If one observes so many off-axis jets, the jet opening angles must be
very small. This may contradict the late jet break data. Finally, the steep dependence between \( L_{R,p} \propto t^{-2/3} \) is difficult to interpret within the off-axis scenario (see also Panaitescu & Vestrand 2010). Alternatively, the jet may have an angular structure (Mészáros et al. 1998; Zhang & Mészáros 2002b; Rossi et al. 2002). In this case, there are ejecta beaming directly toward the observer along the line of sight, and a light curve rising feature is essentially the deceleration feature in that direction. Our interpretation is still valid, and the \( \Gamma_0 - E_{\gamma,\text{iso}} \) correlation gets a new meaning, namely, it reflects the relation between the energy angular structure and the Lorentz factor angular structure.

Within the deceleration interpretation, if one assumes slow cooling at the deceleration time (i.e., \( v_m < v_L \)), the peak luminosity in the optical band can be expressed in the form

\[
L_p \propto \frac{E_{\gamma,\text{iso}}}{\eta(\beta_0 + 1/2)} \Gamma_0^{-3/2} \eta^{-1/2} \theta(\beta_0 + 1/2). 
\]

Applying the \( \Gamma_0 \propto E_{\gamma,\text{iso}}^{1/4} \) correlation, this is translated to

\[
L_p \propto E_{\gamma,\text{iso}}^{1/4} \eta^{-1/2} \theta(\beta_0 + 1/2). 
\]

The observed \( \theta_0 \) ranges in \( 0.5 - 1.0 \) (see Table 3), which gives

\[
L_p \propto E_{\gamma,\text{iso}}^{1.5 - 2.0} \eta^{-1.5}. 
\]

This is roughly consistent with the observed \( L_R - E_{\gamma,\text{iso}} \) correlation (Equation (12)), especially if there is a weak positive correlation between \( E_{\gamma,\text{iso}} \) and \( \eta \). We regard this as another support to the fireball deceleration interpretation discussed in this paper.

5.4. Early Optical Versus X-ray Emission: Different Physical Origins?

The simultaneous observations in the optical and X-ray bands during the early afterglow phase also hold the key to address whether the broadband emission is from the same emission component. Generally, the XRT light curves are composed of a few power-law decaying segments and some erratic flares. Although the X-ray light curves are diverse among bursts, they can be roughly classified into three groups with a large, uniform sample established by XRT. The majority is the so-called canonical XRT light curves characterized by a steep–shallow–normal–steep decay pattern (Zhang et al. 2006; Nousek et al. 2006; O’Brien et al. 2006), although not all the segments show up in every burst (Evans et al. 2009). The second group is composed of those light curves that show a single power-law decay from early to late epochs (Liang et al. 2009; Evans et al. 2009). The third group includes some GRBs that show an “internal plateau” that is followed by a rapid drop with a decay slope steeper than \(-3\) (Liang et al. 2007; Troja et al. 2007; Lyons et al. 2010). The detailed physical processes contributing to the X-ray emission of GRB afterglows remain largely unidentified (see e.g., Zhang 2007 for a review), and their origin might be diverse (Liang et al. 2007). It is clear that the X-ray flares and internal plateaus are of an internal origin.

However, the origin of the canonical light curve is still subject to debate. “Closure”-relation analyses suggest that the normal decay segment following the shallow decay one in the canonical XRT light curves is roughly consistent with the forward shock models (Willingale et al. 2007; Liang et al. 2007), favoring the long lasting energy injection models for the shallow-decay segment. However, the optical/X-ray chromatic behavior around the shallow and normal decay transition time (Panaitescu et al. 2006; Fan & Piran 2006; Liang et al. 2007) suggests that the X-ray and optical emissions are two independent components. Some models attribute the entire X-ray emission to the late emission from the central engine, probably related to the long-term accretion history of the central engine (Ghisellini et al. 2007; Kumar et al. 2008; Cui et al. 2009; Cannizzo & Gehrels 2009), but the consistency with the “closure relation” of the external shock model predictions is not naturally explained in these models. Interestingly, Yamazaki (2009) recently suggested that the X-ray emission might be an independent component prior to the GRB trigger, and that the apparent shallow-to-normal transition is merely a reference time effect.

Liang et al. (2009) systematically studied the canonical X-ray afterglow light curves as observed by Swift/XRT and confirmed that shifting the reference time can indeed stretch the canonical light curves to single power-law light curves. They proposed a unified picture for the physical origin of both the canonical and the single power-law decaying XRT light curves.

As shown in Figure 1, the optical and X-ray light curves are dramatically different at the early epoch, i.e., \( t < 1000 \) s post GRB trigger. This strongly suggests that the radiations from the two energy bands are not from the same component. The correlations between the observables of the prompt gammarays and early optical afterglows shown in Figure 5 strongly suggest that the optical emission is likely the “afterglow” of the GRB fireball (external shock component). This is consistent with the smooth afterglow onset feature observed in the optical band for these GRBs. On the other hand, it also suggests that the early bright X-ray emission is not from the external shock. One natural question would be: where is the external shock X-ray component? Inspecting the details of the X-ray and optical afterglow light curves in Figure 1, we can see that this component is very likely hidden underneath some brighter X-ray emission components in the early epochs (e.g., flares, internal plateaus, or even normal plateaus). Interestingly, one can find an X-ray decay slope similar to that of the optical in the late epochs in half of the GRBs in our sample, including GRBs 050820A, 060418, 060605, 061007, 070318, 070411, 071031, 080319C, 080810, and 081203. We therefore cannot exclude the possibility that the late X-ray and optical emissions share the same external shock origin.

A mixture of different emission components contributing to the observed X-ray emission (Willingale et al. 2007; Liang et al. 2007, 2009; Nardini et al. 2010) also naturally interprets the fact that the afterglow onset is rarely observed in an X-ray afterglow light curve. This would require that other early X-ray components are not bright enough to outshine the external shock component. In fact, we find only 13 out of \( \sim 400 \) cases in the current XRT light curve sample, as shown in Figure 2. With \( \Gamma_0 = 100 - 1200 \) derived from the \( \Gamma_0 - E_{\gamma,\text{iso}} \) relation, we expect that the corresponding observed \( t_p \) is in the range of \( 20 - 1500 \) s for a typical GRB at \( z = 2 \) according to the \( \Gamma_0 - t_{p,z} \) correlation (Equation (17)). In this time period, the observed X-rays are generally dominated by the GRB tail emission or flares. This may be, at least partially, the reason why not many early X-ray light curves show the clear afterglow onset bump signature. Since the optical band is less affected by the other emission components related to the central engine, one naively expects that the X-ray onset cases should have achromatic optical onset feature as well. Unfortunately, the optical/X-ray joint observations in this sample are rare: only GRB 080507 and GRB 080319C have early optical observations. The optical light curve of GRB 080507 is sparse. For GRB 080319C one indeed observes a plausible achromatic onset feature. There is an earlier decay feature in the optical light curve of GRB 080319C. It may be associated with an internal emission component within such an interpretation.
6. CONCLUSIONS

We have extensively searched for the afterglow onset “bump” feature from early afterglow light curves, both in the optical band (through literature survey) and in the X-ray band (through systematically analyzing the Swift/XRT data). Twenty GRBs are identified in the optically selected sample and 12 GRBs are found in the X-ray-selected sample. We fit the onset bumps with a smooth broken power law and measure their characteristics. The rising index \( r \) for most bursts is 1–2, and the decay index \( d \) is 0.44–1.77. These are well consistent with the forward shock models. The peak time \( t_p \) is in \( 10^{-2} \)–\( 10^3 \) s with a median value of \( \sim 380 \) s. The width of the bumps measured at FWHM is \( 10^{-2} \)–\( 10^3 \) s, and the typical rising time \( t_r \) and decaying time \( t_d \) are \( 10^2 \) s and \( 10^3 \) s, respectively. The ratio of \( t_d/t_p \) is narrowly distributed around 0.1–0.3, and the ratio \( t_r/t_d \) has a distribution in the range of 0.3–1. Most GRBs in our optically selected sample have redshift measurements. We analyze pair correlations among the bump characteristics. We find that the pulse width, rising time, decaying time, and the peak time are strongly correlated. Bumps that peak later are dimmer and wider. No correlation between the decay index \( d \) and other parameters is found, but the rising index \( r \) is tightly anti-correlated with both the ratio \( t_r/t_d \) and \( \eta \), although it is not correlated with \( t_r \\) and \( \eta \).

We analyze the relation of the optical afterglow bumps with prompt gamma-ray properties. We find that a GRB with a larger \( \Gamma _{\text{iso}} \) tends to have a brighter optical afterglow and tends to be decelerated by the surrounding medium earlier. These tight correlations strongly suggest an external shock afterglow origin of the early optical emission. Within the framework of the standard forward shock model in a constant density circumburst medium, we calculate the initial Lorentz factor \( \Gamma _0 \) and the deceleration radius \( R_{\text{dec}} \) for the GRBs in the optically selected sample. The derived \( \Gamma _0 \) ranges from 100 to about 600, while \( R_{\text{dec}} \) is narrowly distributed around \( 10^{17} \) cm. Intriguingly, we discover a tight correlation between \( \Gamma _0 \) and \( E_{\gamma, \text{iso}} \). For typical values \( n = 1 \) cm\(^{-3} \) and \( \eta = 0.2 \) (\( \Gamma _0 \) is rather insensitive to the values of \( n \) and \( \eta \)), we obtain the correlation Equation (19). This correlation is very important to understand GRB prompt emission physics and may serve as an indicator of \( \Gamma _0 \) for other long GRBs. In particular, the correlation disfavors the internal shock synchrotron emission model for the GRB prompt emission. With the tight lower limits of \( \Gamma _0 \) of GRBs 080916C and 090902B derived from opacity constraints with Fermi/LAT observations (Abdo et al. 2009a, 2009c), we find that the two long GRBs are also consistent with the correlation in 2σ confidence level, but short GRBs 090510 (Abdo et al. 2009b) is a clear outlier of this relation.

For most of the GRBs in the optically selected sample, the early X-ray afterglow is dominated by emission components unrelated to the generic forward shock. This reinforces the diverse origin of early X-ray afterglows in most GRBs (e.g., Liang et al. 2007, 2009).

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