Gamma-Ray Burst Afterglows

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Abstract

Extended, fading emissions in multi-wavelength are observed following Gamma-ray bursts (GRBs). Recent broadband observational campaigns led by the Swift Observatory reveal rich features of these GRB afterglows. Here we review the latest observational progress and discuss the theoretical implications for understanding the central engine, composition, and geometric configuration of GRB jets, as well as their interactions with the ambient medium.

Key words: Gamma-Ray Bursts, Swift Observatory, X-rays, optical, radio

1. Introduction

Gamma-ray bursts (GRBs) are the most violent explosions in the universe. They are relativistic outflows launched during collapses of massive stars or mergers of compact objects. Regardless of the nature of the explosion, a generic fireball shock model (Rees & Mészáros 1992, 1994; Mészáros & Rees 1993, 1997, for reviews see Piran 1999, 2005; Mészáros 2002, 2006; Zhang & Mészáros 2004) is found successful to interpret the broad GRB phenomenology. According to this model, the ejecta is intrinsically intermittent and unsteady, and is composed of many mini-shells with a wide range of bulk Lorentz factors. Internal shocks (Rees & Mészáros 1994) are likely developed before the global fireball is decelerated by the ambient medium, which are generally believed to be the emission sites of the observed prompt GRB emission. The fireball is decelerated at a larger distance after sweeping enough interstellar medium whose inertia becomes noticeable, and the blastwave gradually enters a self-similar deceleration regime (Blandford-McKee 1976). Upon deceleration, a pair of shocks forms. A long-lived forward shock propagating into the ambient medium gives rise to the long-term broad band afterglow (Mészáros & Rees 1997; Sari et al. 1998); and a short-lived reverse shock propagating into the ejecta itself gives rise to a possible short-term optical/IR flash and a radio flare (Mészáros & Rees 1997, 1999; Sari & Piran 1999a,b). The relativistic ejecta are likely collimated (Rhoads 1999; Sari et al. 1999), and the jets may have substantial angular structures (Zhang & Mészáros 2002; Rossi et al. 2002). This general theoretical framework has been successful to interpret most of the observational data in the pre-Swift era.

The successful launch and operation of NASA’s broadband (gamma-ray, X-ray, UV & optical) GRB mission Swift (Gehrels et al. 2004) opens a brand new era in the GRB study. The prompt slewing capability of the X-Ray Telescope (XRT, Burrows et al. 2005a) and UV-Optical Telescope (UVOT, Roming et al. 2005) allows the satellite to swiftly catch the very early X-ray and UV/optical signals following the GRB prompt emission detected by the Burst Alert Telescope (BAT, Barthelmy et al. 2005a). The precise localizations made by XRT for the majority of the bursts make it possible for ground-based follow up observations of most bursts. We now have unprecedented information about GRB afterglows,
which sheds light onto many outstanding problems in the pre-Swift era (Zhang & Mészáros 2004 for a summary): e.g. central engine, composition and geometric configuration of the GRB fireball, and its interaction with the ambient medium.

2. A canonical lightcurve of X-ray afterglows

One of the major discoveries of Swift is the identification of a canonical X-ray afterglow behavior (Nousek et al. 2006; Zhang et al. 2006; O’Brien et al. 2006, Chincarini et al. 2005; see Fig.1). Although different afterglow lightcurves may vary from one another, they are all composed of several of the five components illustrated in Fig.1.

- Steep decay phase (I): Typically smoothly connected to the prompt emission (Tagliaferri et al. 2005; Barthelmy et al. 2005b), with a temporal decay slope $\sim -3$ or steeper (sometimes up to $\sim -10$, e.g. Vaughan et al. 2006; Cusumano et al. 2006; O’Brien et al. 2006) extending to $\sim (10^2 - 10^3)$s. Usually have a different spectral slope from the later afterglow phases.

- Shallow decay phase (II): Typically with a temporal decay slope $\sim -0.5$ or flatter extending to $\sim (10^3 - 10^4)$s, at which a temporal break is observed before the normal decay phase (e.g. Campana et al. 2005; De Pasquale et al. 2006). There is no spectral evolution across the break.

- Normal decay phase (III): Usually with a decay slope $\sim -1.2$, and usually follows the predictions of the standard afterglow model (Mészáros & Rees 1997; Sari et al. 1998; Chevalier & Li 2000). A systematic test of the afterglow closure-relations (e.g. Table 1 of Zhang & Mészáros 2004) suggests however that a fraction of bursts do not satisfy any afterglow model (Willingale et al. 2006).

- Post Jet break phase (IV): Occasionally observed following the normal decay phase, typically with a decay slope $\sim -2$, satisfying the predictions of the standard jet model (Rhoads 1999; Sari et al. 1999) or the structured jet model (Rossi et al. 2002; Zhang & Mészáros 2002).

- X-ray flares (V): Appear in nearly half of GRB afterglows. Sometimes multiple flares harbor in one GRB. Typically have very steep rising and decaying slopes (Burrows et al. 2005b; Falcone et al. 2006; Romano et al. 2006) with $\delta t/t \ll 1$. Appear in both long-duration (Falcone et al. 2006) and short-duration GRBs (Barthelmy et al. 2005b; Campana et al. 2006a), and both hard GRBs and soft X-ray flashes (Romano et al. 2006). Except for the normal decay and the jet-break phases, all the other three components were not straightforwardly expected in the pre-Swift era. As of the time of writing, the steep decay phase and X-ray flares are better understood, while the shallow decay phase is still a mystery.

2.1. Steep decay phase: tail of the prompt emission

The generally accepted interpretation of the steep decay phase is the tail emission due to the so-called “curvature effect” (Fenimore et al. 1996; Kumar & Panaitescu 2000; Zhang et al. 2006; Panaitescu et al. 2006a; Dyks et al. 2006). The basic assumption of this interpretation is that the GRB emission region is disconnected from the afterglow region (the external shock), and that the emission from the GRB emission region ceases abruptly. This is consistent with the conjectures of internal shocks or other internal dissipation mechanisms (e.g. magnetic fields reconnection, etc). Since it is generally assumed that the ejecta has a conical geometry, the curvature of the radiation front causes a propagation delay for high-latitude emission from the line of sight. Combining with the variation of the Doppler factor at different latitudes, one gets a simple prediction

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1The flare-like signature was seen by Beppo-SAX, but it was interpreted as the onset of the afterglow (Piro et al. 2005).
\[ \alpha = 2 + \beta \]  

for the emission outside the \( \Gamma^{-1} \) emission cone, where the convention \( F_{\nu} \propto t^{-\alpha} \nu^{-\beta} \) is adopted. The salient feature of this interpretation is that it could be directly tested since both \( \alpha \) and \( \beta \) could be measured directly from the observational data, given that two complications are treated properly (Zhang et al. 2006): First, for internal emissions, every time when the central engine restarts, the clock should be re-set to zero. In the log \( - \) log lightcurves, this usually introduces an “artificial” very steep decay if the GRB trigger time (which is usually taken as \( t = 0 \)) significantly leads the time zero point \( (t_0) \) of the corresponding emission episode. Second, the observed decay is the superposition of the curvature decay and underlying afterglow decay from the external shock. One needs to subtract the underlying afterglow contribution before performing the test. The credibility of the curvature effect interpretation to the steep decay phase is that by properly taking into account the two effects mentioned above, the steep decay is consistent with Eq.(1) with \( t_0 \) shifted to the beginning of the last pulse of prompt emission (Liang et al. 2006) at least in some cases.

Besides the standard curvature effect model, other interpretations for the steep decay phase have been discussed in the literature.

- In some cases, the steep-decay slope may be shallower than the expectation of the curvature effect. This would suggest that the central engine may not die abruptly or the shocked region may not cool abruptly, but rather decay with time gradually, leading to a decaying afterglow related to the central engine (Fan & Wei 2005; Zhang et al. 2006). This was taken by Fan et al. (2006) to interpret the abnormal power law decay of GRB 060218 (Campana et al. 2006b).

- Yamazaki et al. (2006) study the curvature effect of an inhomogeneous fireball (mini-jets). They found that the decay tail is generally smooth, but sometimes could have structures, which may interpret the small-scale structure in some of the decay tails.

\[ 2 \]  We notice that for external shock related emissions, taking the GRB trigger time as the time zero point is generally required (Lazzati & Begelman 2006; Kobayashi & Zhang 2006).

\[ 3 \]  It is worth noticing that generally a decay slope steeper than the curvature effect prediction is not allowed, unless the jet is very narrow. Usually, even if the intrinsic temporal decay slope is steeper than Eq.(1), the curvature effect nonetheless takes over to define the decay slope.

- Pe’er et al. (2006) suggest that the emission from the relativistically expanding hot plasma “coconut” associated with the GRB jet could also give rise to the steep decay phase observed by Swift.

Motivated by the discovery of the spectrally evolving tails in GRB 050724 (Campana et al. 2006b) and GRB 060614 (Gehrels et al. 2006; Zhang et al. 2007a), recently Zhang et al. (2007c) performed a systematic time-dependent spectral analysis of 17 bright steep decay tails. They found that while 7 tails show no apparent spectral evolution, the other 10 do. A simple curvature effect model invoking an angle-dependent spectral index cannot interpret the data. This suggests that the curvature effect is not the sole factor to control the steep decay tail phase at least in some bursts. Zhang et al. (2007c) show that some of the spectrally evolving tails may be interpreted as superposition of the curvature effect tail and an underlying central engine afterglow, which is soft but decays “normally”. Such a component has been seen in GRB 060218 (Campana et al. 2006b), which cannot be interpreted by the standard external shock afterglow (Willingale et al. 2006). The strong spectral evolutions in GRB 050724, GRB 060218, and GRB 060614, however, cannot be interpreted with such a model. They are interpreted as internal shock afterglows by Zhang et al. (2007c).

2.2. X-ray flares: restarting the central engine

The X-ray flares have the following observational properties (Burrows et al. 2005b; Chincarini et al. 2007): Rapid rise and fall times with \( \delta t / t_{\text{peak}} \ll 1 \); many light curves have evidence for a same decaying afterglow component before and after the flare; multiple flares are observed in some bursts with similar properties; large flux increases at the flares; typically degrading fluence of flares with time, but in rare cases (e.g. GRB 050502B) the flare fluence could be comparable with that of the prompt emission; flares soften as they progress; and later flares are less energetic and more broadened than early flares. These properties generally favor the interpretation that most of them are not associated with external-shock related events. Rather they are the manifestations of internal dissipations at later times, which requires restarting the GRB central engine (Burrows et al. 2005b; Zhang et al. 2006; Fan & Wei 2005; Ioka et al. 2005; Wu et al. 2006; Falcone et al. 2006; Romano et al. 2006; Laz-
zati & Perna 2006). Compared with the external shock related models, the late internal dissipation models have the following two major advantages (Zhang et al. 2006): First, since the clock needs to be re-set each time when the central engine restarts, it is very natural to explain the very sharp rising and falling lightcurves of the flares. Second, energetically the late internal dissipation model is very economical. While in the refreshed external shock models a large energy budget is needed (the injection energy has to be at least comparable to that already in the blastwave in order to have any significant injection signature, Zhang & Mészáros 2002), the internal model only demands a small fraction of the prompt emission energy to account for the distinct flares.

The leading candidate of the late internal dissipation model is the late internal shock model. In such a model, the collisions could be between the fast shells injected later and the slow shells injected earlier during the prompt phase (e.g. Zou et al. 2006; Staff et al. 2006) or between two shells injected at later times (see Wu et al. 2006 for a categorization of different types of collisions). One concern is whether later collisions between two slow shells injected during the prompt phase could give rise to the observed X-ray flares. This is generally not possible. The internal shock radius can be expressed as

$$R_{is} \sim \frac{d_0}{\beta_f - \beta_s} \sim \frac{\Gamma_i^2 d_0}{\beta_s}$$

where $d_0$ is the initial separation between the two colliding shells, $\beta_f$ and $\beta_s$ are the dimensionless velocities of the fast and slow shells, respectively, and $\Gamma_i$ is the Lorentz factor of the slow shell. The second approximation is valid if $\Gamma_f \gg \Gamma_s$. In order to produce late internal shocks, the two slow shells must both have a low enough Lorentz factor so that at the time of collision they do not collide with the decelerating blastwave. Also in order not to collide with each other earlier, their relative Lorentz factor $\Delta \Gamma$ must be very small. When they collide, the internal energy $[\propto (\Gamma_{sf} - 1) \ll 1]$ is usually too small to give rise to significant emission (where $\Gamma_{sf} \sim (\Gamma_f/\Gamma_s + \Gamma_s/\Gamma_f)/2$ is the relative Lorentz factor between the two shells). Should such a collision occur, most likely it has no interesting observational effect (see Lazzati & Perna 2006 for more detailed discussion on this issue). Generally, in the internal shock model the observed time sequence reflects the time sequence in the central engine (Kobayashi et al. 1997). As a result, the observed X-ray flares $(10^2 - 10^3)$s after the prompt emission must imply that the central engine restarts during this time span, say, as late as days after the prompt emission is over.

The late internal dissipation model of X-ray flares is also tested by Liang et al. (2006). The same logic of testing the steep decay component is used. The starting assumption is that the decay of X-ray flares are controlled by the curvature effect after the abrupt cessation of the internal dissipation, so that Eq.(1) is assumed to be valid. After subtracting the underlying forward shock afterglow contribution, Liang et al. (2006) search for the valid zero time points ($t_0$) for each flare to allow the decay slope satisfying the requirement of the curvature effect model. If the hypothesis is correct, $t_0$ should be generally before the rising segment of each flare.

The testing results are impressive: Most of the flares indeed have their $t_0$ at the beginning of the flares. This suggests that the internal dissipation model is robust for most of the flares. It is worth emphasizing that even the late slow bump at around 1 day following the short GRB 050724 (Barthelmy et al. 2005c; Campana et al. 2006a) satisfies the curvature effect model, suggesting that the central engine is still active even at 1 day after the trigger. This is also consistent with the late Chandra observation of this burst (Grupe et al. 2006a) that indicates that the afterglow resumes to the pre-flare decay slope after the flare.

Having identified the correct model for the flare phenomenology, one is asked about a fundamental question: how to restart the central engine. No central engine models in the pre-Swift era have specifically predicted extended activities far after the prompt emission phase. Prompted by the X-ray flare observations, the following suggestions have been made recently, and none is proved by robust numerical simulations at the moment.

- Fragmentation or gravitational instabilities in the massive star envelopes. King et al. (2005) argued that the collapse of a rapidly rotating stellar core leads to fragmentation. The delay of accretion of some fragments after the major accretion lead to X-ray flares following collapsar-related GRBs.
- Fragmentation or gravitational instabilities in the accretion disk. Observations of GRB 050724 (Barthelmy et al. 2005c; Campana et al. 2006a; Grupe et al. 2006a), a short GRB associated with an elliptical host galaxy that is consistent with the compact star merger progenitor model, reveal that it is also followed by several X-ray flares starting from 10s of seconds all the way to $\sim 10^3$s. The properties of these X-ray flares are similar to those in long GRBs. The requirement that
both long and short GRBs should produce X-ray flares with similar properties prompted Perna et al. (2006) to suggest that fragmentation in the accretion disk, the common ingredient in both long and short GRB models, may be the agent for episodic accretion that powers the flares.

- Magnetic barrier. Based on the MHD numerical simulations in other contexts and theoretical arguments, Proga & Zhang (2006) argue that the magnetic barrier near the black hole may act as an effective modulator of the accretion flow. The accretion flow can be intermittent in nature due to the role of magnetic fields. This model does not require the flow being chopped (e.g. due to fragmentation or gravitational instabilities) at larger radii before accretion, although in reality both processes may occur altogether. The magnetic barrier model is in accordance with the magnetic origin of X-ray flares based on the energetics argument (Fan et al. 2006c).

- NS-BH merger. Flares in GRB 050724 (Barthelmy et al. 2005c) pose great challenge to the previous compact star merger models. Numerical simulation of NS-NS mergers typically gives a short central engine time scale (0.01-0.1)s, if the final product is a BH-torus system (Aloy et al. 2005). In order to account for the late time flares in 050724, Barthelmy et al. (2005c) suggest a possible NS-BH merger progenitor system. Numerical simulations of BH-NS merger systems have been performed. Although X-ray flares at 100s of seconds or later still challenge the model, extended accretion over several seconds could be reproduced (Faber et al. 2006; cf. Rosswog 2005).

- NS-NS merger with a postmerger millisecond pulsar. Dai et al. (2006a) argue a possible solution for the extended X-ray flares following merger-type GRBs. Numerical simulations have shown that the product of a NS-NS merger may not be a BH (Shibata et al. 2005), if the NS equation-of-state is stiff. Instead, the final product may be a differentially-rotating massive neutron star. If the initial magnetic fields of the NS is not strong, the $\alpha - \Omega$ dynamo action would induce magnetic explosions that give rise to late internal shocks to produce X-ray flares (Dai et al. 2006a).

- Multi-stage central engine. Gao & Fan (2006) and Staff et al. (2006) proposed multi-stage central engine models to interpret X-ray flares.

2.3. Shallow decay phase: still a mystery

The shallow decay phase could follow the steep decay phase or immediately follow the prompt emission (O’Brien et al. 2006; Willingale et al. 2006). It is very likely related to the external-shock-origin afterglow. However, the origin of this shallow decay phase is more difficult to identify, since there exist several different possibilities that are not easy to differentiate among each other from the X-ray observations. The fact that the spectral index does not change across the temporal break from the shallow decay phase to the normal decay phase rules out the models that invoke crossing of a spectral break across the band. The nature of the break should be then either hydrodynamical or geometrical.

Following models have been discussed in the literature.

- Energy injection invoking a long-term central engine. The most straightforward interpretation of the “shallower-than-normal” phase is that the total energy in the external shock continuously increases with time. This requires substantial energy injection into the fireball during the phase (Zhang et al. 2006; Nousek et al. 2006; Pannestes 2006). There are two possible energy injection schemes (Zhang et al. 2006; Nousek et al. 2006). The first one is to simply invoke a long-lasting central engine, with a smoothly varying luminosity, e.g. $L \propto t^{-q}$. In order to give interesting injection signature $q < 1$ is required; otherwise the total energy in the blastwave essentially does not increase with time. Such a possibility is valid for the central engines invoking a spinning down pulsar (Dai & Lu 1998; Zhang & Mészáros 2001; Fan & Xu 2006) or a long-lasting BH-torus system (MacFadyen et al. 2001). One possible signature of this scenario that differentiates it from the varying-$\Gamma$ model discussed below is that a strong relativistic reverse shock is usually expected, if at the shock interacting region the $\sigma$-parameter (the ratio between the Poynting flux and the kinetic flux) is degraded to below unity (Dai 2004; Yu & Dai 2006). Alternatively, if $\sigma$ is still high at the shock region, the reverse shock may be initially weak, but would still become relativistic if the engine lasts long enough (i.e. this is effectively a rather thick shell, Zhang & Kobayashi 2005). The observational data suggest a range of $q$ values with typical value $q \sim 0.5$. This is different from the requirement of the ana-
lytical pulsar model ($q = 0$). However, numerical calculations suggest that a pulsar model can fit some of the XRT lightcurves (Fan & Xu 2006; De Pasquale et al. 2006; Yu & Dai 2006).

- Energy injection from the ejecta with a wide $\Gamma$-distribution. This model invokes a distribution of the Lorentz factor of the ejecta with low-$\Gamma$ ejecta lagging behind the high-$\Gamma$ ones, and only piling up to the blastwave when the high-$\Gamma$ part is decelerated (Rees & Mészáros 1998). In order to produce a smooth power law decay, the $\Gamma$-distribution needs to be close to a power law with $M(>\Gamma) \propto \Gamma^{-s}$. A significant energy injection requires $s > 1$. The temporal break around $(10^3 – 10^4) \text{s}$ suggests a cutoff of Lorentz factor around several $10^4$, below which $s$ becomes shallower than unity (Zhang et al. 2006). Granot & Kumar (2006) have used this property to constrain the ejecta Lorentz factor distribution of GRBs within the framework of this model. The reverse shock of this scenario is typically non-relativistic (Sari & Mészáros 2000), since the relative Lorentz factor between the injection shell and the blastwave is always low when the former piles up onto the latter.

- Delayed energy transfer to the forward shock. Analytically, the onset of afterglow is estimated to be around $t_{\text{dec}} = \max(t_\gamma, T)$, where $t_\gamma \sim 5 \text{s} (E_{K,5}/n)^{1/3} (\Gamma_0/300)^{-8/3} (1 + z)$ is the time scale at which the fireball collects $\Gamma^{-1}$ of the rest mass of the initial fireball from the ISM, and $T$ is the duration of the explosion. The so-called “thin” and “thick” shell cases correspond to $t_\gamma > T$ and $t_\gamma < T$, respectively (Sari & Piran 1995; Kobayashi et al. 1999). Numerical calculations suggest that the time scale before entering the Blandford-McKee self-similar deceleration phase is long, of order several $10^3 \text{s}$ (Kobayashi & Zhang 2006). This suggests that it takes time for the kinetic energy of the fireball to be transferred to the medium. In a high-$\sigma$ fireball, there is no energy transfer during the propagation of a reverse shock (Zhang & Kobayashi 2005). Although energy transfer could happen after the reverse shock disappears, this potentially further delays the energy transfer process (although detailed numerical simulations are needed to verify this). The shallow decay phase may simply reflect the slow energy transfer process from the ejecta to the ambient medium. This model (e.g. Kobayashi & Zhang 2006) predicts a significant curvature of the lightcurves. This is consistent with some of the lightcurves that show an early “dip” before the shallow decay phase. For those cases with a straight shallow decay lightcurve, one needs to incorporate the steep decay tail to mimic the observations.

- Off-beam jet model. Geometrically one can invoke an off-beam jet configuration to account for the shallow decay. Eichler & Granot (2006) show that if the line of sight is slightly outside the edge of the jet that generates prominent afterglow emission, a shallow decay phase can be mimicked with the combination of the steep decay GRB tail. Toma et al. (2006) discussed a similar model within the framework of the patchy jet models.

- Two-component jet model. A geometric model invoking two jet components could also fit the shallow-decay data, since additional free parameters are invoked (Granot et al. 2006; Jin et al. 2006).

- Precursor model. Ioka et al. (2006) suggest that if there is a weak precursor leading the main burst, a shallow decay phase can be produced as the main fireball sweeps the remnants of the precursor.

- Varying microphysics parameter model. One could also invoke evolution of the microphysics shock parameters to reproduce the shallow decay phase (Ioka et al. 2006; Fan & Piran 2006; Granot et al. 2006; Panaitescu et al. 2006b).

- Dust scattering model. Shao & Dai (2006) suggest that small angle scattering of X-rays by dust could also give rise to a shallow decay phase under certain conditions.

Can different possibilities be differentiated by the more abundant data? It seems to be a challenging task. The author is inclined to the first three interpretations on the above list. For the two energy injection models, one expects different reverse shock signatures (i.e. relativistic reverse shock for the long-term central engine model and non-relativistic reverse shock for the varying-$\Gamma$ model). This would give different radio emission properties at early times. On the other hand, the uncertainty of the composition of the central engine outflow (e.g. the $\sigma$ parameter) would make the reverse shock signature of the former model more obscured. The delayed energy transfer model (the third one on the above list) is the simplest. If it is correct, the so-called shallow decay phase is nothing but a manifestation of the onset of afterglow (Kobayashi & Zhang 2006). The peak time can be then used to estimate the onset Lorentz factor of the fireball (which is $\sim 100$ or less for standard parameters). This might be the case for at least some of the bursts.
3. Optical observations

In the pre-Swift era, the afterglow observations were mainly carried out in the optical and radio bands. The late time optical/radio observations have been focused on identifying temporal breaks in the lightcurves, which are generally interpreted as the “jet breaks” (see Frail et al. 2001; Bloom et al. 2003; Ghirlanda et al. 2004; Dai et al. 2004; Friedman & Bloom 2005; Liang & Zhang 2005 for compilations of the jet break data in the pre-Swift era).

Broad-band modeling was carried out for a handful of well observed bursts (Panaitescu & Kumar 2001, 2002; Yost et al. 2003), and the data are generally consistent with the standard external shock afterglow model. In some cases, very early optical flashes have been discovered (e.g. GRB 990123, Akerlof et al. 1999; GRB 021004, Fox et al. 2003a; GRB 021211, Fox et al. 2003b; Li et al. 2003a), which are generally interpreted as emission from the reverse shock (Sari & Piran 1999a; Mészáros & Rees 1999; Kobayashi & Sari 2000; Kobayashi 2000; Wang et al. 2000; Fan et al. 2002; Kobayashi & Zhang 2003a; Zhang et al. 2003; Wei et al. 2003; Kumar & Panaitescu 2003; Panaitescu & Kumar 2004; Nakar & Piran 2004). Early radio flares have been detected in a sample of GRBs (Frail et al. 2003), which are also attributed to the reverse shock emission (Sari & Piran 1999a; Kobayashi & Sari 2000; Soderberg & Ramirez-Ruiz 2003). The expectation for Swift before the launch has been that UVOT would collect a good sample of early afterglow lightcurves to allow a detailed study of GRB reverse shocks.

3.1. Early optical afterglows: where is the reverse shock emission?

In the Swift era, UVOT has been regularly collecting optical photons ∼ 100s after the burst triggers for most GRBs. Ground-based robotic telescopes (e.g. ROTSE-III, PAIRITEL, RAPTOR, P60, TAROT, Liverpool, Faulkes, KAIT, PROMPT, etc) have promptly observed most targets whenever possible. A good list of early optical detections have been made. However, the majority of bursts have very dim or non-detection of optical afterglows (Roming et al. 2006a). This suggests that in most cases the reverse shock, if any, is not significant.

Figure 2 displays the theoretically predicted early optical afterglow lightcurves (Zhang et al. 2003) in the ISM model. The thick solid line shows two peaks: the first peak followed by ∼ t−2 decay is the reverse shock emission peak time, which is typically at the shock crossing time (t_{dec}). The second peak followed by ∼ t−1 is the forward shock peak, which corresponds to the time when the typical synchrotron frequency ν_{ms} crosses the optical band. Depending on parameters, the forward shock peak could be buried below the reverse shock component (the thin solid line). One therefore has two cases of optical flashes: Type I (rebrightening) and Type II (flattening).

A unified study of both reverse shock and forward shock emission suggests that Type I lightcurves should be generally expected, if the shock microphysics parameters (ε_e, ε_B, p, etc) are the same in both shocks. On the other hand, these microphysics parameters may not be the same in both shocks. In particular, if the central engine is strongly magnetized, as is expected in several progenitor models, the outflow likely carries a primordial magnetic field, which is likely amplified at the shocks. It is then possible to have R_B = (ε_{B,r}/ε_{B,f})^{1/2} ≫ 1 in some cases. This is actually the condition to realize the Type II lightcurves (Zhang et al. 2003). In order to interpret the bright optical flash and the subsequent Type II lightcurves in GRB 990123 and GRB 021211, one typically requires R_B ∼ 10 or more (Fan et al. 2002; Zhang et al. 2003).
The $\epsilon_B$ treatment is based on a purely hydrodynamical treatment of shocks with magnetic fields put in by hand. Invoking a strong magnetic component in the reverse shock region raises the necessity to treat the dynamics more carefully with a dynamically important magnetic field. Zhang & Kobayashi (2005) studied the reverse shock dynamics and emission for an outflow with an arbitrary $\sigma$ parameter. They found that the most favorable case for a bright optical flash (e.g. GRB 990123 and GRB 021211) is $\sigma \sim 1$, i.e. the outflow contains roughly equal amount of energy in magnetic fields and baryons. This is understandable: For a smaller $\sigma$, the magnetic field in the reverse shock region is smaller, and the synchrotron emission is weaker (see also Fan et al. 2004). For a larger $\sigma$, the magnetic field is dynamically important, whose pressure dominates the outflow region. The shock becomes weak or does not exist at all (when $\sigma$ is large enough).

The lack of bright optical flashes such as those observed in GRB 990123 and GRB 021211 is therefore not surprising. In order to have a bright Type II flash, one needs happen to have an outflow with $\sigma \sim 1$, while both larger and smaller $\sigma$’s would lead to not very significant optical flashes. Even without additional suppression effects, a non-relativistic shock with $\sigma = 0$ would generally give a reverse shock peak flux below the forward shock peak level (Kobayashi 2000; Nakar & Piran 2004; Zhang & Kobayashi 2005). On the other extreme, a high-$\sigma$ flow would lead to very weak reverse shock emission or no reverse shock at all (Zhang & Kobayashi 2005). Thus the tight early UVOT upper limits (Roming et al. 2006a) are not completely out of expectation.

Additional mechanisms to suppress optical flashes have been discussed in the literature. Beloborodov (2005) argues that Compton cooling of electrons by the prompt MeV photons may be a way to suppress the optical flashes. Kobayashi et al. (2006) suggest that a dominant synchrotron-self-Compton process in the reverse shock region would suppress the synchrotron optical emission. Li et al. (2003b) and McMahon et al. (2006) suggest a pair-rich reverse shock with weak optical emission.

Despite of the general disappointments, several bright optical flashes have been detected in the Swift era, which could be generally interpreted within the reverse/forward shock model discussed above. The IR afterglow of GRB 041219A (Blake et al. 2005) is well modeled by a Type I (rebrightening) lightcurve (Fan et al. 2005b). Another Type II (flattening) lightcurve was detected from GRB 060111B (Klotz et al. 2006). Marginal reverse shock signatures may be present in GRB 050525A (Blustin et al. 2006; Shao & Dai 2005), GRB 050904 (Gendre et al. 2006; Wei et al. 2006), GRB 060117 (Jelinek et al. 2006) and GRB 060108 (Oates et al. 2006). Data suggest a second type of optical flashes, which tracks the gamma-ray lightcurves (for GRB 041219A, Vestrand et al. 2005). These optical flashes are likely related to internal shocks (Mészáros & Rees 1999), probably neutron rich (Fan et al. 2005b).

There are however cases that clearly show no reverse shock component in the bright optical afterglows. GRB 061007 (Mundell et al. 2006; Schady et al. 2006b) is such a case. Reaching a peak magnitude $< 11$ (similar to 9th magnitude of GRB 990123), both the X-ray and optical lightcurves show single power law decaying behavior from the very beginning ($\sim 80$ s after the trigger). This suggests a strong external forward shock emission with enormous kinetic energy (Mundell et al. 2006) or a structured jet with very early jet break (Schady et al. 2006b). The reverse shock emission in this case is believed to peak at the radio band (Mundell et al. 2006).

3.2. Bumps and flares

Wiggles and bumps have been observed in several pre-Swift GRB optical afterglows (e.g. GRB 021004, Holland et al. 2003; GRB 030329, Lipkin et al. 2004). Models to interpret these variabilities usually invoke external shock related processes, such as density fluctuation, inhomogeneous jets, refreshed shocks, or multiple component jets (Lazzati et al. 2002; Heyl & Perna 2003; Nakar et al. 2003; Berger et al. 2003a; Granot et al. 2003; Ioka et al. 2005). Early optical lightcurves may contain neutron decay signatures (Beloborodov 2003; Fan et al. 2005a). Ioka et al. (2005) pointed out that some optical fluctuations are difficult to interpret within any external shock related schemes, and they require reactivation of the central engine.

That erratic X-ray flares generally require late central engine activities raises the question whether some optical flashes/flares are also due to the same origin (but softer and even less energetic, e.g. Zhang 2005). Recent optical afterglow observations reveal that anomalous optical afterglows seem to be the norm (Stanek et al. 2006; Roming et al. 2006c). Although some of them could be accommodated
within the external shock related models, some optical flares do show similar properties as X-ray flares (e.g. $\delta t/t < 1$, Roming et al. 2006c), which demands late central engine activities. For example, the optical fluctuations detected in the short GRB 060313 optical afterglows (Roming et al. 2006b) may be better interpreted as due to late central engine activities than due to density fluctuations (Nakar & Granot 2006).

Efforts to model optical flares using the late internal shock model have been carried out recently (Wei et al. 2006; Wei 2006). The results suggest that for plausible parameters, even the traditional reverse shock optical flashes such as those in GRB 990123, GRB 041219A and GRB 060111B could be interpreted within the late internal shock model.

3.3. Optically bright vs. optically dark; optically luminous vs. optically dim

In the previous optical follow up observations, GRBs are generally divided into two categories, optically bright and optically dark ones (e.g. Jakobsson et al. 2004; Rol et al. 2005). The latter typically account for $\sim 50\%$ of the total population. The discovery of the early optical flash of GRB 021211 (Fox et al. 2003b; Li et al. 2003) in the HETE-2 era had led to the ansatz that as long as observations are performed early enough, most dark bursts are not dark. This is now proven not the case (Roming et al. 2006a). Among the possible reasons of optical darkness, foreground extinction, circumburst absorption, and high redshift are the best candidates.

Among the optically bright GRBs, it is intriguing to discover that there are two sub-categories, namely optically luminous and optically dim (Liang & Zhang 2006; Nardini et al. 2006; Kann et al. 2006). The rest-frame lightcurves of GRBs with known redshifts are found to follow two “universal” tracks. The rest-frame 10-hour luminosities of the bursts with known redshifts show a clear bimodal distribution. The optically dim bursts all appear to locate at redshifts lower than $\sim 1$ (Liang & Zhang 2006). The origin of such a clear dichotomy is unknown, but is likely related to different total explosion energy involved in the two groups of bursts.

5 Swift UVOT does not detect optical afterglows for $\sim 67\%$ of the Swift bursts. Combining with ground-based follow ups, the non-detection rate is $\sim 45\%$ (P. Roming, 2006, private communication).

4. Global properties

Combining the broad-band afterglow properties for different types of GRBs, one can peer into some global properties of GRB afterglows.

4.1. GRB radiative efficiency

One interesting question is the GRB radiative efficiency, which is defined as $\eta = E_\gamma/(E_\gamma + E_K)$, where $E_\gamma$ and $E_K$ are isotropic gamma-ray energy and kinetic energy of the afterglow, respectively. The reason why $\eta$ is important to understand explosion mechanism is that it is related to the energy dissipation mechanism of the prompt emission, which is not identified. The standard picture is internal shock dissipation, which typically predicts several percent radiative efficiency (Kumar 1999; Panaitescu et al. 1999, cf. Beloborodov 2000, Kobayashi & Sari 2001). Other mechanisms (e.g. magnetic dissipation) may have higher efficiencies although detailed prediction is not available. It is of great interest to estimate $\eta$ from the data, which can potentially shed light onto the unknown energy dissipation process.

In order to estimate $\eta$, reliable measurements of both $E_\gamma$ and $E_K$ are needed. While $E_\gamma$ could be directly measured from the gamma-ray fluence if the GRB redshift is known, the measurement of $E_K$ is not trivial, which requires detailed afterglow modeling. In the pre-Swift era, attempts to estimate $E_K$ and $\eta$ using late time afterglow data have been made (e.g. Panaitescu & Kumar 2001, 2002; Freedman & Waxman 2001; Berger et al. 2003b; Lloyd-Ronning & Zhang 2004). The Swift XRT observations suggest a substantial shallow decay phase in a good fraction of GRBs (Fig.1). If this is due to energy injection, then $E_K$ is a function of time. The $\eta$ values measured using the late time data are no longer reliable. For a constant energy fireball, ideally early afterglows may be used to study radiative loss of the fireball. However the shallow decay phase due to energy injection smears the possible signature and makes such a diagnosis difficult.

A systematic analysis of GRB radiative efficiencies using the first hand Swift data is carried out by Zhang et al. (2007b). Similar analyses using second-hand data for smaller samples of bursts were carried out by Fan & Piran (2006) and Granot et al. (2006). The conclusions emerging from these studies suggest that in most cases the efficiency is very high (e.g. $> 90\%$) if $E_K$ right after the burst is adopted.
However, using $E_K$ at a later time when the injection process is over one typically gets $\eta \sim$ several percent. The nature of the shallow decay phase is therefore essential to understand the efficiency. For example, if the shallow decay phase is due to continuous energy injection, the GRB radiative efficiency must be very high - causing problems to the internal shock model. If, however, the shallow decay is simply due to the delay of energy transfer into the forward shock, the GRB radiative efficiency is just the right one expected from the internal shock model. One interesting finding of Zhang et al. (2007b) is that X-ray flashes may not be intrinsically less efficient GRBs, as was expected in the pre-Swift era (Soderberg et al. 2004; Lloyd-Ronning & Zhang 2004). Analyses show that at the early deceleration time, XRFs are as efficient as harder GRBs (see also Schady et al. 2006a).

One of major breakthroughs made by Swift is the discoveries of the afterglows of short-duration GRBs and identifications of their host galaxies (Gehrels et al. 2005; Fox et al. 2005; Villasenor et al. 2005; Hjorth et al. 2005; Barthelmy et al. 2005c; Berger et al. 2005). These observations suggest that short GRBs likely have distinct progenitor systems, on the other hand, short GRBs are rather similar to long GRBs (Zhang et al. 2007b; see also Bloom et al. 2006 and Lee et al. 2005). This suggests that both types of GRBs share the same radiation physics.

4.2. Where are the jet breaks?

If GRB outflows are collimated into the typical jet angle $\theta_j$, an achromatic afterglow steepening break should be observed in all energy bands at the time when the bulk Lorentz factor of the jet satisfies $\Gamma^{-1} = \theta_j$ (Rhoads 1999; Sari et al. 1999). This time is called jet break time $t_j$.

Identifying GRB jet breaks in the afterglow lightcurves is essential to understand the geometric configuration and the total energetics of the jets. In the pre-Swift era, a list of “jet breaks” have been “identified” in the optical (sometimes X-ray and radio) afterglows (see Frail et al. 2001; Bloom et al. 2003; Ghirlanda et al. 2004; Friedman & Bloom 2005; Liang & Zhang 2005 for compilations of the jet break data). We use quotation marks here since the “smoking-gun” feature of the jet breaks, i.e. the achromatic behavior, was not robustly established in any of these bursts. The best case was GRB 990510 (Harrison et al. 1999), in which clear multi-color optical breaks were discovered, which are consistent with being achromatic. The radio data are also consistent with having a break around the same time. However, based on radio data alone, one cannot robustly fit a break time that is consistent with the optical break time (D. Frail, 2006, private communication). Most of other previous jet breaks were claimed using one-band data only, mostly in optical, and sometimes in X-ray or radio. With these “jet break times” $t_j$, several empirical relations have been discussed in the literature.

- Frail relation: Frail et al. (2001) found that the beaming-corrected gamma-ray energy is essentially constant, i.e. $E_{\gamma,iso}^{1/2} = E_p \propto$ const. Since the standard jet model predicts $t_j \propto E_{\gamma,iso}^{1/3}$, this relation is generally consistent with $E_{\gamma,iso} \propto t_j^{-1}$.

- Ghirlanda relation: Ghirlanda et al. (2004) found that the beaming-corrected gamma-ray energy is not constant, but is related to the rest-frame spectral peak energy ($E_p$) through $E_p \propto E_{\gamma,j}^{2/3}$. Again expressing $E_{\gamma,j}$ in terms of $E_{\gamma,iso}$ and $t_j$, this relation is effectively $E_p \propto E_{\gamma,iso}^{1/2} t_j^{1/2}$. Notice that the Ghirlanda relation and the Frail relation are incompatible with each other.

- Liang-Zhang relation: Liang & Zhang (2005) took one step back. They discard the jet model, and only pursue an empirical relation among three observables, namely $E_p$, $E_{\gamma,iso}$ and the optical band break time $t_b$. The relation gives $E_p \propto E_{\gamma,iso}^{0.52} t_b^{0.64}$. It is evident that if $t_b$ is interpreted as the jet break time, the Liang-Zhang relation is rather similar to the Ghirlanda relation. However, the former has the flexibility of invoking chromatic temporal breaks across different bands. So violating the Ghirlanda relation in other wavelengths (e.g. in the X-ray band, Sato et al. 2006) does not necessarily disfavor the Liang-Zhang relation.

It has been highly expected that the multi-wavelength observatory Swift would clearly detect achromatic breaks in some GRBs to verify the long-invoked GRB jet scenario. The results are however discouraging. After detecting nearly 200 bursts, no “textbook” version jet break is yet detected in any GRB. The lack of detections may be attributed partially to the intrinsic faintness of the Swift afterglows, and partially to the very low rate of late time optical follow-up observations. Achromatic breaks
were indeed observed in some bursts, but none satisfy the salient features expected in the jet model. For example, GRB 050801 (Rykov et al. 2006) and GRB 060729 (Grupe et al. 2006b) have an early achromatic break covering both the X-ray and optical bands. However, the break is the transition from the shallow decay phase to the normal decay phase, which is likely an injection break rather than a jet break. GRB 050525A (Blustin et al. 2006) has an achromatic break in X-ray and optical bands, which might be interpreted as a jet break. However, the post-break temporal indices in both X-ray and optical bands are too shallow to comply with the $\propto t^{-p}$ prediction. An achromatic jet break was claimed for GRB 060526 (Dai et al. 2006b). However, the post break indices for both X-ray and optical bands are significantly different from each other, so that more complicated jet models are needed to accommodate the data.

In most other cases, data seem to disfavor (or at least not to support) the existence of jet breaks. The data also cast doubts on the previous identified jet breaks. These pieces of evidence are collected in the following.

- Optical follow up of GRB 060206 reveals a clear temporal break that would be regarded as a typical jet break should the X-ray have not been collected (Monfardini et al. 2006). However, X-ray data show a remarkable single power law decay without any evidence of a break at the optical break time (Burrows 2006).

- Many other X-ray afterglows also show remarkable single power law decays extending to very late times (10 days or later, Burrows 2006). The lower limits of the beaming-corrected gamma-ray energy of many bursts already greatly exceed the standard energy reservoir value suggested by Frail et al. (2001) and Bloom et al. (2003) (Burrows 2006).

- Based on the Ghirlanda relation, Sato et al. (2006) have searched for expected jet breaks of three Swift bursts in the X-ray band with null results. This suggests that Ghirlanda relation is not a common relation satisfied by most bursts. This fact however does not disfavor the Liang-Zhang relation, since an optical break may still exist at the expected time if the breaks are chromatic. Late time optical observations are needed to test whether the Liang-Zhang relation is generally valid/violated for most bursts.

It is worth mentioning that in several cases, the X-ray data are consistent with having a jet break. These include GRBs 050315, 050814, 050820A, 051221A and 060428A (see Burrows 2006 for a review). In particular, late Chandra ToO observations of the short GRB 051221A reveal a possible jet break, suggesting collimation in merger type GRBs (Burrows et al. 2006).

4.3. A new paradigm of temporal breaks?

The data seem to suggest that there might exist other types of temporal breaks at least for some bursts that are not related to jet breaks. A very interesting feature of the afterglow breaks is that the X-ray breaks systematically lead the optical breaks, which in turn systematically lead the radio breaks. This fact, along with the chromatic breaks in both X-rays (e.g. Panaitescu et al. 2006b) and optical (e.g. Monfardini et al. 2006), drives the author to speculate an ad hoc scenario to interpret these temporal breaks as well as the Liang-Zhang ($E_{\gamma,\text{iso}} - E_p - t_b$) relation. In this scenario, the spectral break in the prompt gamma-ray emission ($E_p$) and the chromatic temporal breaks in the afterglow lightcurves may be all related to a same electron energy distribution break that rolls down from high energy to low energy. Initially the break is in the gamma-ray band, which defines the $E_p$ in the prompt emission spectrum. Later this break moves to the X-ray band in $\sim (10^3 - 10^4)$ s, giving rise to the early injection-like breaks in some bursts. The break keeps moving down to the optical band around a day, which can account for the pre-Swift optical breaks that were interpreted as jet breaks. Later it moves to the radio band in $\sim 10$ days. Such a scenario gives a natural link between $E_p$ and the optical break time $t_b$ in the Liang-Zhang relation, which is otherwise difficult to explain.

There are several problems with this scenario, however. First, it requires that for the bursts of interests the prompt emission and the afterglows are from the same emission component. This is in contradiction with the Swift finding that prompt emission and X-ray flares are of the internal origin while afterglows are of external origin (e.g. Zhang et al. 2006). Nonetheless, maybe some bursts indeed satisfy this requirement. If so, either the prompt emission of these bursts are of external origin, or more possibly, the afterglows of these bursts are of internal origin, i.e. they are the central engine afterglows. Second, a natural expectation of this scenario is that the spectral indices before and after the breaks should
be different. This seems to contradict with the X-ray data that suggest no spectral evolution across the early break is observed. However, the latest systematic study of temporal breaks (Willingale et al. 2006) suggest that spectral changes in some breaks are observed. It is interesting to look closer whether those bursts with spectral evolution are also consistent with both prompt emission and afterglow being from the same emission component, and therefore might satisfy the temporal break scenario suggested here.

Other than these difficulties, this new scenario seems to be able to account for chromatic breaks observed in some afterglows. A hard test of this scenario is to find some bursts that have a break crossing through the X-ray, optical and radio bands in turn. Although no clear example is available in the Swift data sample, the previous GRB 030329 may satisfy the requirement of this model. It has been claimed that there are two “jet breaks” in this burst (Berger et al. 2003a): an early optical break and a later radio break. These two breaks were used to argue a two-component jet model for this burst. Within the scenario proposed here, the two breaks are simply the same break rolling over the optical and radio bands at different times.

Similar to the Liang-Zhang relation that connects $E_p$ with the optical break time $t_{b,\text{opt}}$, this scenario also predicts a correlation between $E_p$ and the X-ray break times $t_{b,X}$. Such a correlation seems to have been revealed in the Swift data (Willingale et al. 2006).

5. Conclusions: a global picture of GRB afterglows

Swift opens a new window to study the global properties of GRB afterglows. Although some model predictions are verified by the new data (it is impressive that many X-ray afterglows satisfy the closure relations predicted in simple external shock models), what we gain more from the Swift observations are problems that challenge the previous theoretical framework. It is evident that our view about GRB afterglows is now much broader than in the pre-Swift era. We tentatively draw the following conclusions.

- What we call afterglows actually include two distinct components: one is from the traditional external shock, the other is from the central engine. It is evident that some flaring components (most X-ray flares and probably some optical flares) are of internal origin, marking the reactivation of the central engine. However, one may be driven to accept that some of the smooth power law decay components may also reflect the emission from the central engine. This is relevant to some XRT lightcurves that do not satisfy any closure relation, and to some chromatic breaks that are difficult to accommodate within the standard external shock models. If some of the power-law decay lightcurves directly reflect the luminosity output of the central engine, one has to accept that the GRB central engine is long lived, not only erratically (to produce flares), but in some cases also continuously (to produce the smooth decay component). The latter is consistent with the first energy injection model (the refreshed shock model) that invokes a long-term central engine.

- The most puzzling question is the nature of GRB afterglow temporal breaks. The current data suggest that some breaks are still consistent with being jet breaks, but in a lot of other cases conflicts present. The pre-Swift relations invoking jet breaks (Frail and Ghirlanda relations) are not confirmed by the Swift data. Evidence of chromatic breaks in both X-ray and optical bands is accumulating. At least for some bursts, one may require new interpretations (such as the one proposed in §4.3) for the observed temporal breaks. Since the nature of breaks is one of the major puzzles in the concurrent GRB study, late time optical follow up observations are strongly encouraged to reveal whether optical breaks as predicted by the $E_p - E_{\gamma,\text{iso}} - t_{b,\text{opt}}$ (Liang-Zhang) relation still exist despite of the apparent lack of X-ray breaks at the same epoch. This would make a strong case for whether the previous “jet breaks” are in fact chromatic breaks.

- It is now high time to perform systematic data analyses of the abundant Swift GRB data to peer into the global properties of the bursts. While one can still gain knowledge from special individual events (such as GRB 060218 and GRB 060614), for most of the “normal” bursts, only global statistical properties can serve to improve our understanding of GRBs. Issues need to clarify include the properties and nature of broadband flares/bumps, temporal breaks, the compatibility of data with closure relations, etc. Some extensive efforts in these directions have just commenced (e.g. Willingale et al. 2006; Chincarini et al. 2006).
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