Gamma-Ray Burst Early Afterglows

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Abstract. The successful launch and operation of NASA's *Swift* Gamma-Ray Burst Explorer open a new era for the multi-wavelength study of the very early afterglow phase of gamma-ray bursts (GRBs). GRB early afterglow information is essential to explore the unknown physical composition of GRB jets, the link between the prompt γ-ray emission and the afterglow emission, the GRB central engine activity, as well as the immediate GRB environment. Here I review some of the recent theoretical efforts to address these problems and describe how the latest *Swift* data give answers to these outstanding questions.

Keywords: Gamma-ray burst; afterglow; X-ray; UV; optical; *Swift*
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INTRODUCTION

Our understanding of cosmological gamma-ray bursts (GRBs) have been greatly advanced during the past several years. Before the launch of the *Swift* satellite (on Nov. 20, 2004), there have been a few outstanding questions in the study of GRBs that call for more definite answers (see e.g. [1] for more detailed discussions). For example, where is the prompt gamma-ray emission emitted, at the external shock just like the afterglows or at an "inner" radius due to shock or magnetic dissipation? What is the physical composition of the GRB jets, baryonic or magnetic? If they are baryonic, are there free neutrons in the fireball? How does the GRB central engine work? Does it become dormant when the prompt gamma-ray emission is over? What is the immediate environment of GRBs, a constant density (ISM) medium or a massive stellar wind? Are short duration GRBs different from the long duration GRBs? The *Swift* satellite [2], thanks to its capability of promptly slewing the on-board X-Ray Telescope (XRT) [3] and the UV-Optical Telescope (UVOT) [4] to the GRB target triggered by the Burst Alert Telescope (BAT) [5], is an ideal mission to address these questions. The X-ray afterglow data[1] retrieved as early as less than $\sim$ 100 s after the GRB trigger would give valuable information on the transition between the prompt gamma-ray emission phase and the afterglow phase. In the optical band, it is highly expected that the early afterglow lightcurve should include the contribution of a short-lived reverse shock component. The late afterglows, on the other hand, originate from the forward shock and therefore reflect the emission from the

[1] Theoretically speaking an afterglow is the signal emitted when the fireball is decelerated by the ambient medium which lasts much longer than the prompt emission itself. In this sense, some X-ray signals detected after the prompt gamma-rays (e.g. X-ray flares [6]) are not afterglows. Here we follow the convention of defining an afterglow as the electromagnetic signals detected after the prompt gamma-ray emission is over.

circumburst medium. The reverse shock component is therefore very precious since it directly carries the information of the GRB outflow itself, and is valuable to diagnose the physical composition of the fireball jets. By carefully diagnosing the early afterglow data, one can also retrieve valuable information of the GRB central engine and the properties of the circumburst environment. *Swift* has indeed been very fruitful in addressing these problems during the first several months of its operation. Here I summarize some of the latest theoretical work on GRB early afterglows, and discuss how the models are compared against the abundant *Swift* data.

OPTICAL BAND: EXPECTATIONS

The standard forward-reverse shock model

A generic GRB model [7, 8, 9] suggests that regardless of the mechanism of the explosion and the property of the central engine, a relativistic ejecta (fireball) expanding into the space would be eventually decelerated by the circumburst medium. Usually a pair of shocks form, i.e. a long-lived forward shock propagating into the ambient medium and a short-lived reverse shock propagating into the fireball itself [9, 10, 11]. Since the shocked fireball ejecta is typically denser than the shocked medium by a factor of $\sim \Gamma_0$, the initial Lorentz factor of the fireball, the typical emission frequency of the reverse shock component is $\sim \Gamma_0^2$ times smaller than that of the forward shock component[2]. As a result, the reverse shock emission peaks in the UV/optical/IR band according to the standard theory.

Before *Swift* is launched, there have been already extensive observational efforts using ground-based robotic telescopes to catch the very early optical afterglow of GRBs. Although most of these searches only place upper limits, some observations yielded well-monitored early afterglow lightcurves. In particular, GRB 990123 [12] and GRB 021211 [13, 14] show impressively similar early lightcurve behavior marked by a clear transition from roughly $\propto t^{-2}$ to roughly $\propto t^{-1}$. GRB 021004 shows a different behavior [15]. In any case, models invoking the reverse shock have been proposed to interpret these early optical behaviors [10, 11, 16, 17].

A unified treatment of both the reverse shock and the forward shock components [18] suggests that if the ambient medium density is constant (e.g. ISM) in general one expects two lightcurve peaks (Fig.1). The reverse shock flux peaks at the time when the reverse shock crosses the shell [19], while the forward shock peaks at the time when the typical synchrotron frequency ν_m crosses the optical band [20]. If the shock parameters (ϵ_e, ϵ_B and p) are similar to each other in both shocks, generally one expects a lightcurve with two distinct peaks detectable, and the lightcurve is categorized as the "re-brightening" type [18] (thick line in Fig.1). On the other hand, since the ejecta composition could be rather different from that of the circumburst medium, it is quite plausible that the shock parameters are different in both shocks. In particular, if the central engine is

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[2] This is valid for the so-called thin-shell regime, i.e. the burst duration T is shorter than the fireball deceleration time defined by the total energy E and the density n.

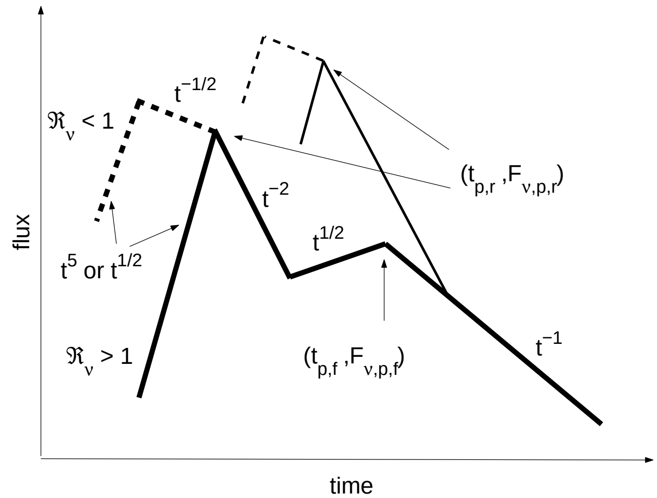

FIGURE 1. Typical early optical afterglow lightcurves (ISM case). Two types are identified: the re-brightening case (thick), and the flattening case (thin) which usually requires a strongly magnetized reverse shock. From [18].

strongly magnetized, the magnetic fields in the reverse shock region could be (much) stronger than those in the forward shock region. By introducing a parameter $\mathscr{R}_B \equiv B_r/B_f$ (where B_r and B_f are the magnetic field strengths in the reverse and the forward shock, respectively), it is found that [18] the forward shock peak is usually buried beneath the reverse shock component only when $\mathscr{R}_B \gg 1$ (see also [21, 22, 23, 24]). The lightcurve is categorized as the steep ($\propto t^{-2}$) to flat ($\propto t^{-1}$) transition, or the "flattening" type [18] (thin line in Fig.1). The well-studied cases of GRB 990123 and GRB 021211 belong to such a category, i.e. the reverse shock interpretation requires a strongly magnetized central engine. The "re-brightening" type lightcurve has been used to interpret GRB 021004 [16] and GRB 041219A [25].

The early optical afterglow lightcurves in a wind medium has been studied in [26, 27, 28, 29, 30]. It is noticed that in such an environment the reverse shock region usually overlaps the prompt gamma-ray photon beam [31]. The Inverse Compton cooling is therefore significant [32], which would modify the reverse shock emission behavior significantly and leads to additional observational signatures in the GeV range [31].

Diagosing GRB fireball composition

Baryonic or magnetic? Since a strongly magnetized central engine was inferred at least in GRB 990123 and GRB 021211 [18, 21, 22], a direct question is whether the GRB outflows are dominated by strong magnetic fields (i.e. a Poynting flux). In other words, how large is the σ parameter, which is defined as the ratio between the Poynting flux and baryonic kinetic energy flux in the outflow? Previous treatments of the reverse shock dynamics/radiation are purely hydrodynamical. Magnetic fields are included only through an equipartion parameter ϵ_B. In order to treat magnetic fields self-consistently and study the reverse shock emission for an outflow with a wide range of σ values, one needs to start with the MHD shock jump conditions. This has been done in [33] (see also [34] for the discussions for $\sigma \leq 1$). According to [33], the reverse shock peak flux increases with σ when $\sigma \leq 1$. This is mainly because for $\sigma \leq 1$ the dynamics of the flow is essentially not modified compared with the purely hydrodynamical case. On the other hand, ε_B in the reverse shock region keeps increaseing with σ, so that the synchrotron emission becomes progressively stronger. It reaches a peak around $\sigma \sim 1$, with an $\mathscr{R}_B \sim (3\varepsilon_{B,f})^{-1/2} \sim 18\varepsilon_{B,f,-3}$. This is roughly the $\mathscr{R}_B$ value inferred in GRB 990123 [18], which explains why the bright optical flash seen in GRB 990123 is rare since it requires the most optimized σ value (around unity) to achieve a large $\mathscr{R}_B$. As σ becomes larger than unity, the flow becomes Poynting flux dominated. The reverse shock becomes progressively weaker and it disappears when σ is as high as ~ 100. The reason is that given a same initial Lorentz factor Γ_0, the typical internal energy density in the forward shock is at most $e_{2,\max} = 4\Gamma_0^2 m_p c^2$, and the pressure at the contact discontinuity is at most $p_{2,\max} = e_{2,\max}/3$. As σ becomes higher and higher, the magnetic pressure behind the contact discontinuity (p_3) would become larger and larger, and eventually exceeds $p_{2,\max}$ so that no reverse shock could form. Notice that the disappearance of reverse shock in the high-σ regime is not due to that a shock can not exist in a high-σ flow (in fact, the shock suppression factor essentially does not decrease in the high-σ regime, [33]), but is rather due to the maximum available forward shock pressure defined by Γ_0. A large fraction of *Swift* bursts were not seen by UVOT at very early epochs [35]. This suggests that the reverse shock emission is strongly suppressed. Among other possibilities, a Poynting-flux-dominated model is a plausible interpretation. Within this scenario, the early afterglow is expected to be intrinsically dim initially since the bulk of the energy contained in the magnetic fields is not transferred to the ISM by the time the reverse shock disappears [33]. This seems to be consistent with the fact that some early-UVOT-dark bursts have a relatively faint X-ray afterglow flux level at 1 hr after the trigger, resulting in a very high apparent gamma-ray emission efficiency [35].

Neutron-rich fireball? If the fireball is dominated by baryons, it has been suggested that a substantial fraction of baryons are free neutrons and the decay of these neutrons would lead to interesting observing features in the early afterglow phase [36, 37]. Detailed calculations have been carried out [38]. For an ISM-type medium, the leading neutrons decay, drag the ISM and shock into the medium. This "neutron-decay-trail ejecta" is decelerated by the ISM, and is eventually caught up with by the trailing proton shell [38]. As a result, the neutron signature in the ISM case is essentially an energy injection signature, which has been extensively modeled before (e.g. [39]). In a wind medium, the direct emission from the neutron decay trail may become important. However, the "overlapping effect" with the gamma-ray photon flow makes the signature not very significant [38].

Besides leaving imprints in the early afterglows, free neutrons would also play an important role in the internal shock phase (e.g. [40, 41]). The neutron-rich internal shocks could result in strong optical emission associated with the prompt gamma-rays due to much weaker synchrotron self-absorption at the neutron decay radius, which could interpret the apparent association between gamma-ray and optical emission detected in GRB 041219A ([25, 42, 43]).

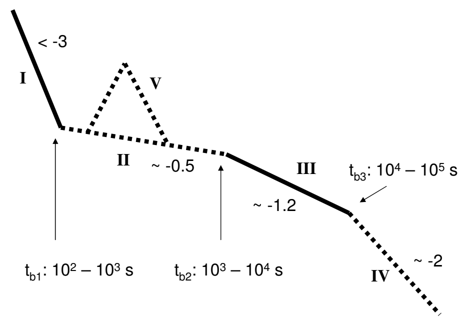

FIGURE 2. A canonical early X-ray afterglow lightcurve inferred from the *Swift* XRT observations. From [48].

Swift data. Because of the previous positive detections of the optical flashes in GRB 990123 and GRB 021211 [12, 13, 14] and intensive theoretical investigations of the GRB reverse shock, it has been highly expected that the *Swift* UVOT would record many nice early afterglow lightcurves that allow us to study the reverse shock in greater detail. Indeed a fraction of *Swift*-triggered bursts has early optical afterglows recorded by UVOT and other groundbased robotic telescopes, and the reverse shock component has been identified in GRB 041219A [25] and possibly also in GRB 050525A [44, 45]. Yet it is still out of one's expectation that the majority of the UVOT bursts are "dark" from the very beginning, despite of the prompt slews and the deep exposures [35]. It might be that at least some GRBs are Poynting flux dominated, so that the reverse shock emission component is suppressed [33].

X-RAY BAND: SURPRISES

Contrary to the optical band, the X-ray band was only sparsely studied in the early afterglow phase before the launch of *Swift*. This is because only little early X-ray data were available, and because the reverse shock emission is not expected to be important in the band. It turns out that *Swift* XRT detected an X-ray afterglow for essentially every burst (in contrast to UVOT), and it brings several surprises to the GRB workers, since the new phenomena are not straightforwardly expected in the pre-*Swift* era.

After inspecting a sample of early X-ray afterglow data (e.g. [46, 47], one can draw a synthetic X-ray afterglow lightcurve [48] (see Fig.2). This lightcurve includes 5 components: I. an early steep decay; II. a follow-up shallower-than-normal decay; III. a normal decay; IV. a jet break; and V. one or more X-ray flares. Three time breaks (t_{b1}, t_{b2} and t_{b3}) separate the segments I, II, III and IV. Not every burst has all these components, but they are all common features. The segments III (normal decay) and IV (jet break) are expected based on previous late optical afterglow observations. However, the other three components are regarded as "surprises".

Surprise 1: steep decay. A rapid decay component is evident in the early X-ray lightcurves of the majority of the *Swift* bursts [49]. In some bursts this component is smoothly connected to the spectrally-extrapolated BAT lightcurve [50], and it could be generally interpreted as the "tail emission" of the prompt emission due to the so-called "curvature effect" [51]. In some cases, a mismatch between the steep decay and the BAT lightcurve is evident, but it could be well the tail emission of the X-ray flares [6]. The curvature-effect suggests that the temporal decay index α and the spectral index β should satisfy $\alpha = 2+\beta$ [51]. In order to accomodate the data, additional effects (e.g. shifting the time zero point to the last pulse in the prompt emission or the X-ray flare, substracting the underlying forward shock component, etc.) are needed [48]. Alternatively, the steep decay may be also a result of the central engine activity [52, 48]. This distinct component suggests that the GRB prompt emission (and the X-ray flare emission) originate from a different location than that of the afterglow, i.e. likely at an "internal" radius within the deceleration radius [53]. The large contrast between the prompt emission component and the afterglow component (connected with the steep decay component) also suggests a very high gamma-ray emission efficiency [48].

Surprise 2: shallow-than-normal decay. In a good fraction of the *Swift* bursts, the decay slope in the afterglow phase (after the steep tail emission ends) is shallower than what is expected in the standard afterglow model with a constant energy. The total energy in the fireball needs to increase with time, so that the fireball is continuously refreshed for a much longer time than the burst duration [48]. This corresponds to Segment II in Fig.2. There are three physical possibilities that could give rise to such a refreshed shock. 1. The central engine keeps pumping energy with a reduced rate, e.g. $L(t) \propto t^{-q}$ [54]; 2. The energy injection from the central engine is brief but the ejecta have a wide range of Lorentz factors with a power-law distribution [55]; 3. The outflow is Poynting-flux-dominated, so that the magnetic field takes a longer time to be transferred into the medium [33]. A successful model must interpret why the injection index $q \sim 0.5$ is inferred from the data [48, 47] and why there is a well-defined epoch when the injection ceases abruptly (see [48] for more discussions).

Surprise 3: X-ray flares. Yet another surprise is the X-ray flares detected in nearly half of the *Swift* GRBs [6, 56, 57]. Although a weak flare (e.g. in GRB 050406) may be interpreted as the synchrotron self Compton emission in the reverse shock region [58] under well balanced conditions, the general properties of the flares (e.g. the large amplitude in GRB 050502B, rapid rising and falling lightcurves, more than one flares in one burst) strongly suggest that the correct mechanism is the late central engine activity [48] (see also [6, 52]). Even more surprisingly, after the breakthrough of localizing short, hard GRBs and building a close link between the short bursts and the compact star merger models [59, 60], extensive X-ray flares are discovered in the short burst GRB 050724 [60]. The observed late central engine activity in compact star mergers pose great challenge to the merger modelers. In particular, it is argued that the central engine mechanism to power flares in the merger scenario must be of magnetic origin, and the X-ray flares are expected to be linearly polarized [61]. Numerical simulations with full MHD effects (e.g. [62]) are desirable in the models of the GRB central engine.

SPECULATIONS

With the current abundant early afterglow data collected by *Swift* and other ground-based optical telescopes, it is now evident that the GRB early afterglow phase is more complicated than what one could imagine in the pre-*Swift* era. The simplest reverse+forward shock picture, although applicable in the interpretations, is inconclusive.

One speculation is that we seem to be collecting evidence that at least some GRBs are strongly magnetized or even Poynting-flux-dominated. The tight early UVOT upper limits [35], the apparent high gamma-ray efficiency in some bursts [35], the flat injection phase identified in the X-ray afterglow lightcurves of a group of bursts [48, 47], as well as the argument regarding the X-ray flare mechanism [61], all seem to be consistent with such a picture (e.g. [33]). More data and more detailed modeling are needed to verify such a speculation.

Another speculation is related to X-ray flares. Before the discovery of the X-ray flares following GRBs, there has been no serious thought about such softer and weaker flares at later times. With what we observe now, one may boldly imagine the existence of even softer flares. Are there optical flares associated with the X-ray flares or even not associated with the X-ray flares? In particular, is the bright 9-mag optical flash detected in GRB 990123 actually an optical flare due to the GRB central engine activity[63]? This comes back to the original suggestion of the internal shock origin of the optical flash [11]. With the new information collected recently, such an intriguing possibility is worth re-investigating.

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