

“LATE PROMPT” EMISSION IN GAMMA-RAY BURSTS?

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ABSTRACT

The flat decay phase in the first 10^2 – 10^4 s of the X-ray light curve of gamma-ray bursts (GRBs) has not yet been convincingly explained. The fact that the optical and X-ray light curves are often different, with breaks at different times, makes problematic any explanation based on the same origin for both the X-ray and optical fluxes. We here assume that the central engine can be active for a long time, producing shells of decreasing bulk Lorentz factors Γ . We also assume that the internal dissipation of these late shells produces a continuous and smooth emission (power law in time), usually dominant in X-rays and sometimes in the optical. When Γ of the late shells is larger than $1/\theta_j$, where θ_j is the jet opening angle, we see only a portion of the emitting surface. Eventually, Γ becomes smaller than $1/\theta_j$, and the entire emitting surface is visible. Thus, there is a break in the light curve when $\Gamma = 1/\theta_j$, which we associate with the time at which the plateau ends. After the steeply decaying phase that follows the early prompt, we see the sum of two emission components: the “late-prompt” emission (due to late internal dissipation), and the “real afterglow” emission (due to external shocks). A variety of different optical and X-ray light curves are then possible, explaining why the X-ray and the optical light curves often do not track each other (but sometimes do), and often they do not have simultaneous breaks.

Subject headings: gamma rays: bursts — radiation mechanisms: general — X-rays: general

Online material: color figure

1. INTRODUCTION

One of the puzzling results of the *Swift* satellite (Gehrels et al. 2004) is the discovery that the 0.3–10 keV X-ray light curve of gamma-ray bursts (GRBs) is much more complex than previously thought in the pre-*Swift* era. After a steep decline of the flux [$F(t) \propto t^{-\alpha_1}$, with $\alpha_1 \sim 3$ –5; Tagliaferri et al. 2005], which is most commonly interpreted as off-axis radiation of a switching-off fireball (see, e.g., Kumar & Panaitescu 2000), the flux decay becomes shallow [$F(t) \propto t^{-\alpha_2}$, with $\alpha_2 \sim 0.2$ –0.8], up to a break time of 10^3 – 10^4 s (Willingale et al. 2007, hereafter W07), after which the flux decays “normally” [$F(t) \propto t^{-\alpha_3}$ with $\alpha_3 \sim 1$ –1.5; Nousek et al. 2006], i.e., in a similar way as that observed in the pre-*Swift* era. In addition, several bursts show flares superposed to this power-law evolution (Burrows et al. 2005), leading Fan & Wei (2005) and Lazzati & Perna (2007) to suggest a long-lasting central engine. Unpredicted beforehand, the complex structure of the X-ray light curve, characterized by a steep-flat-steep behavior, has been interpreted in several ways (for reviews, see, e.g., Panaitescu 2007; Granot 2007; Zhang 2007), none of which seems conclusive. The three main possibilities already proposed (but there are more; see the review by Zhang 2007) are (1) energizing of the forward shock by the arrival of shells being produced late (with large Γ s), or just after the prompt phase (with small Γ s); (2) changing microphysical parameters, assuming that the efficiency of the forward shock to produce radiation increases with time; (3) off-axis jets, whose prompt and early afterglow radiation is not fully beamed toward the observer. Note that the spectral slope does not change across the temporal break from the shallow decay phase to the normal decay phase, ruling out the crossing of a spectral break across the band. This favors instead a hydrodynamical or geometrical nature of the break. All these ideas do not obviously distinguish between X-

ray and optical radiation, which should have the same origin. As a consequence, the light curves in both bands should be similar, contrary to what is observed in several cases (see, e.g., Panaitescu et al. 2006; Panaitescu 2007).

These difficulties recently led Uhm & Beloborodov (2007) and Grenet et al. (2007) to consider the possibility that the X-ray plateau emission is not due to the forward shock, but to the reverse shock running into ejecta of relatively small Lorentz factors. This, however, requires an appropriate Γ -distribution of the ejecta and also the suppression of the X-ray flux produced by the forward shock.

Here we make the alternative proposal that the plateau phase of the X-ray emission (and sometimes even of the optical) is due to a “late-prompt” mechanism: after the early prompt (the prompt that we are used to) there may be a tail of activity of the central engine, producing for a long time (i.e., days) shells of progressively lower power and bulk Lorentz factor. The dissipation process during this and the early phases can occur at similar radii. The total energetics involved in this late activity phase is smaller than (and at most comparable to) the energetics of the early phase, but diluted on a much longer time. The reason for the shallow decay phase, and for the break ending it, is that the Γ -factor is decreasing, allowing one to see an increasing portion of the emitting surface until all of it is visible.

2. LATE PROMPT EMISSION?

Assume that the central engine, after having emitted most of the power in the usual duration of what we call “prompt” emission, continues to create shells of much smaller power, but for a much longer time. For simplicity, let us call “early prompt” and “late prompt” the two phases of activity. By contrast, we call “real afterglow” the emission produced in the forward shock created by the interaction of the shells with the circumburst medium.

The early prompt emission is due to internal dissipation of shells of large Γ -factors (changing erratically) and energy due

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to, for example, internal shocks (Rees & Mészáros 1994), or interactions with the funnel of the progenitor star (Thompson 2006; Thompson et al. 2006), or some form of magnetic reconnection (e.g., Spruit et al. 2001).

We suggest that the late prompt emission can be due to the same dissipation processes but by shells created at late times with smaller Γ and much lower power. The radiation can then be produced at distances relatively close to the central engine (even less than 10^{13} – 10^{14} cm), in a different region where the shells, produced during the early prompt, interacts with the circumburst medium producing the real afterglow. Note that a smaller Γ implies less Doppler time contraction and therefore a less pronounced variability during the late prompt. Furthermore, if Γ is decreasing with time, a new effect appears. In fact, when $\Gamma > 1/\theta_j$, the emission surface seen by the observer is of the order of $(R/\Gamma)^2$ (here R is the distance from the black hole where dissipation takes place, and θ_j is the jet opening angle) and becomes $(\theta_j R)^2$ when $\Gamma \leq 1/\theta_j$. In the same way as in the afterglow case, we should then see a steepening of the light curve when the central engine produces shells with $\Gamma \sim 1/\theta_j$. This should occur at the time t_a , in a similar way as the jet break time t_j for the afterglow. According to this scenario, there is a link between t_a and t_j : both are times at which $\Gamma = 1/\theta_j$, but they refer to two different processes.

The plateau phase of the X-ray emission is characterized by a power-law decay $L(t) \propto t^{-\alpha_2}$, followed by a steeper decay $L(t) \propto t^{-\alpha_3}$. The end of the plateau phase occurs at t_a , and the transition is smooth. If j' is the bolometric emissivity in the comoving frame, we have

$$\begin{aligned} L(t < t_a) &\sim \pi \left(\frac{R}{\Gamma}\right)^2 \Delta R' \Gamma^2 j'(t) \propto t^{-\alpha_2}, \quad \Gamma > 1/\theta_j, \\ L(t \geq t_a) &\sim \pi (\theta_j R)^2 \Delta R' \Gamma^2 j'(t) \propto t^{-\alpha_3}, \quad \Gamma \leq 1/\theta_j. \end{aligned} \quad (1)$$

Assuming that $j'(t)$ is with constant slope before and after t_a , we have $t^{-\alpha_3} \propto \Gamma^2 t^{-\alpha_2}$. Therefore, we find $\Gamma \propto t^{-\Delta\alpha/2}$, with $\Delta\alpha \equiv \alpha_3 - \alpha_2$. This behavior should be appropriate after the time t_* , characterizing the start of the late prompt phase of emission. Finally, we have

$$\Gamma = \Gamma_* \left(\frac{t}{t_*}\right)^{-\Delta\alpha/2}. \quad (2)$$

Since $\langle\alpha_2\rangle = 0.6 \pm 0.3$ and $\langle\alpha_3\rangle = 1.25 \pm 0.25$ (Panaitescu et al. 2006), $\Delta\alpha/2$ is of the order of 0.33 ± 0.2 . This means that the bulk Lorentz factor, at the beginning of the late prompt phase (t_*), is of the order of³

$$\Gamma_* = \theta_j^{-1} \left(\frac{t_a}{t_*}\right)^{\Delta\alpha/2} \sim \frac{46}{\theta_{j,-1}} \left(\frac{t_{a,4}}{t_{*,2}}\right)^{1/3}, \quad (3)$$

which is smaller than what is usually assumed for the early prompt emission. The barion loading of the late shells can be estimated assuming a given efficiency η for the dissipation process leading to the radiation produced in the plateau phase. After t_a , when we see the entire emitting surface, the jet kinetic power per unit solid angle $L_{\text{kin}} = \Gamma \dot{M} c^2 \sim 2L_X/(\theta_j^2 \eta)$, and then

$$\dot{M} = \frac{2L(t > t_a)}{\eta \theta_j^2 \Gamma c^2} \propto t^{-(\alpha_2 + \alpha_3)/2}, \quad (4)$$

which gives approximately $\dot{M} \propto t^{-1}$, with a large dispersion (the dependence is the same also for the plateau phase). The total mass in the late ejecta is relatively small, again most comparable with what can be estimated for the ejecta of the early prompt. This is because, although the Γ -factors are smaller, the total energetics of the late prompt shells is smaller than the one of the early prompt. This agrees with the findings of W07 that the total radiated energy of the late shells (which is called X-ray afterglow in that paper) is, on average, a factor of ~ 10 smaller than the early prompt. Therefore, if η of the early and late shells is similar, we do not expect a big effect from the possible refreshed shocks. We also expect that the late shells reach the front-forward shock at very different times. This is because the late shells are produced at later and later times, and also because the later the shell is produced, the smaller its bulk Lorentz factor, and the longer the time needed to reach the shock front, which is decelerating by the interaction with the circumburst medium. The refreshing effect is long-lasting but diluted. For the same reasons, we expect that the reverse shock is also long-lasting but diluted and therefore not contributing much to the total flux. To see this, assume for illustration a circumburst density with a windlike profile. Calling t_i the time (after the trigger) at which a late shell is created, and t_d the deceleration time, we find that at the observed time t the front shock and the i -th late shell are at distances R_s and R_i , respectively, given by

$$R_s = c t \Gamma^2 = c \Gamma_0^2 \left(\frac{t}{t_d}\right)^{-1/2} = c \Gamma_0^2 (t t_d)^{1/2}, \quad (5)$$

$$R_i = c(t - t_i) \Gamma_i^2, \quad (6)$$

where Γ_0 is the initial Lorentz factor of the early shells. Late shells are assumed not to decelerate until they catch up to the front shock. Equating the two above radii, we have that the i th shell reaches the front shock at the time t_c :

$$t_c \sim \frac{\Gamma_0^4}{\Gamma_i^4} t_d, \quad \text{if } t_c \gg t_i. \quad (7)$$

For $t_d = 100$ s, t_c ranges from 1600 s ($\Gamma_0/\Gamma_i = 2$) to $t_c = 10^6$ s ($\Gamma_0/\Gamma_i = 10$). Since the decrease of the bulk Lorentz factor is associated with a decrease of the kinetic power, we have some effects only for the first refreshed shocks, at times of the order of thousands of seconds, but not later.

2.1. The Real Afterglow

In the pre-*Swift* era, it was generally believed that the real afterglow should contain at least a comparable amount of energy (in the emitted radiation) of the prompt, that it should start a few tens to hundreds of seconds after the trigger, and that the energy band containing most of the emission is the X-ray band [since its energy spectrum $F(\nu) \propto \nu^{-1}$ indicates that the peak in $\nu F(\nu)$ is within or close the X-ray band].

The prediction of the start time of the afterglow seems well confirmed in two cases: GRB 060418 and GRB 060607, as shown in Molinari et al. (2007), thanks to ground-based near-IR observation by the Rapid Eye Mount telescope. Quite remarkably, the X-ray light curve in these two cases does not track the near-IR, confirming that, although the afterglow theory can correctly explain what is seen in the optical, we need another component to explain the X-ray flux. We also conclude that (1) the real afterglow X-ray component is much weaker

³ We use the notation $Q_x = 10^x Q$, in cgs units.

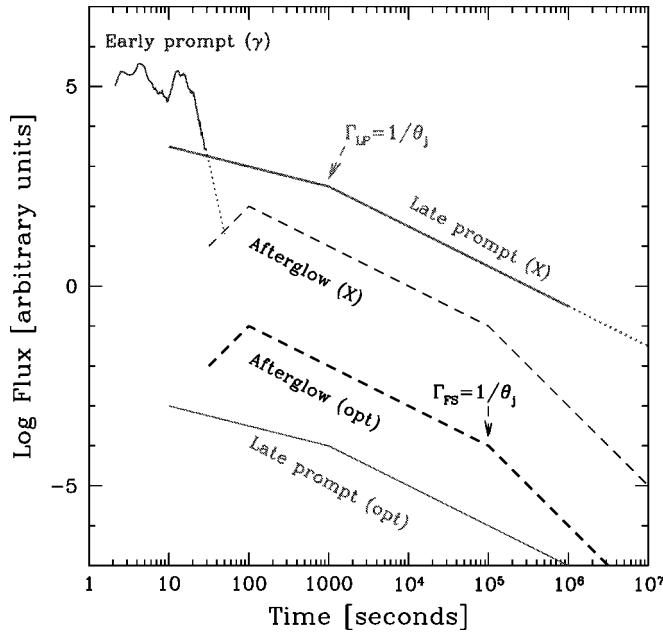


FIG. 1.—Schematic illustration of the different components contributing to the X-ray and optical light curves, as labeled. Scales are arbitrary. The case illustrated here is only one (likely the most common) possible case (see text), when the X-ray flux is dominated by late prompt emission (*solid line*; the dotted line corresponds to an extrapolation at very late times), while the optical flux is dominated by the real afterglow (*dashed line*). Γ_{LP} and Γ_{FS} indicate the Γ of the late shells and the forward shocks, respectively. [See the electronic edition of the Journal for a color version of this figure.]

than thought before, (2) the X-ray band is likely not the band where most of the afterglow energy is, and (3) the total energetics of the real afterglow is much smaller than thought before.

A weak afterglow can result if the microphysical parameters ϵ_e , ϵ_B , at least for the first afterglow phases, are much smaller than commonly thought. Alternatively, the fireball can have a small kinetic energy, as a result of a very efficient prompt phase, that was able to convert a large fraction of the fireball energy into radiation. Furthermore, the radiation produced by the real afterglow should be mostly in the IR-optical, not in the X-ray band.

There is a spectral transition between the varying and generally hard slope of the hard X-ray emission and a more stable and generally softer slope of the later X-ray emission. In W07 the distributions of the spectral index β_x of the prompt and the plateau phase are broad, but a slight narrowing around a value $\beta_x \sim 1$ for the plateau is visible. We propose that this is not due to the prompt/afterglow transition but is instead associated with the transition between the early prompt phase, characterized by large Γ -factors changing erratically, and the late prompt phase characterized by smaller Γ decreasing monotonically.

Note also that the pre-*Swift* observations of the X-ray afterglow should be reinterpreted; in many cases, what is observed even days after the trigger time should be late prompt, not real afterglow, emission.

2.2. Flares

The flares occurring mainly in X-ray (Burrows et al. 2007) but sometimes also in the optical light curve have been associated with internal dissipation (internal shocks) either by late shells, or by shells produced within the first early prompt phase, but moving with a small Lorentz factor. In our framework, the most likely possibility is that a flare is produced by

a late shell, moving with a somewhat larger Lorentz factor than the shells created just earlier. Thus, there will be a chain of interactions between this (faster-than-average) shell and the slower previous ones, and this mechanism can be efficient in converting the kinetic energy of the shell into radiation. Due to the different Doppler contractions of time, late flares should also last longer than early ones. Alternatively, the flares could flag periods of enhanced activity of the central engine, able for some time (i.e., tens or hundreds of seconds) to produce shells (or a continuous flow) of higher energy.

3. DISCUSSION

The scenario proposed here allows the explanation of various GRB properties that are puzzling and mysterious.

In general, the X-ray flux can receive contributions from the steep part of the early prompt phase, the late prompt emission, and from the decelerating early shells that are producing the real afterglow emission. The late prompt emission, in the optical-UV bands, may be reduced if the main radiation process is multiple Comptonization of UV/soft X-ray seed photons, or by self-absorption if it is synchrotron radiation. The real afterglow emission, instead, should produce synchrotron (and self-Compton) radiation in both the X-ray and in the optical bands. Focusing on the plateau and later phases, we may have a complex behavior:

1. The X-ray flux is dominated by late prompt emission, while the optical is dominated by the real afterglow. In this case the light curves in the two bands are independent and show no simultaneous break. In particular, the jet break time is possibly seen in the optical but not in the X-rays.
2. Both the X-ray and the optical fluxes are dominated by late prompt emission. In this case the two light curves are similar, they may have simultaneous breaks (at the time t_a), and the jet break time (due to real afterglow emission) can be masked. The dominance of the late prompt emission may, however, end after some time, beyond which the real afterglow can become visible.
3. Both the X-ray and the optical fluxes are dominated by real afterglow emission. This is the case foreseen before *Swift*. The light curves should have an achromatic jet break, should track one another, and they should not show the break at t_a .

The first case is sketched in Figure 1. While the other two cases can also occur, the case of a late prompt emission dominating in the optical but not in the X-rays seems contrived.

In terms of total energetics, the scenario proposed here may be the least demanding for explaining what is observed. In fact, in the refreshed shock scenario, the plateau phase is flat because the shock running into the circumburst medium is energized by the arrival of shells with kinetic energies that largely overtake the energy of the first shells, which have contributed to the early prompt emission. Alternatively, in the increasing ϵ_e , ϵ_B scenario, the radiation produced during the plateau phase is a very tiny fraction of the carried kinetic energy. Instead, interpreting the plateau phase as late prompt emission, we note that the extra energy created by the central engine in the late phase is less than (or at most comparable to) the total energetics of the shells responsible for the early prompt emission. If the radiative efficiency of the early prompt is large, we can also explain the weakness of the real afterglow emission, since the kinetic energy of the fireball, remaining after the early prompt phase, may be relatively small.

Our scenario is not based on a detailed model of how the central engine works. The following ideas should then be con-

sidered as speculations to be studied in future work. After the black hole formation following the core collapse of the progenitor star, the equatorial core material that failed to form the black hole in the first place can form a very dense accreting torus, which can sustain a strong magnetic field, which in turn extracts the rotational energy of the black hole. This accretion phase could correspond to the early prompt phase of the burst. After this phase, some fallback material may also be accreted. This phase of “late accretion” can last for a longer time, with a density of the accreting matter smaller than in the early phases. If so, the magnetic field that this matter can sustain is weaker than before, with a corresponding smaller power extracted from the black hole spin. This may well correspond to production of shells of smaller Γ -factors. These shells can dissipate part of their energy with the same mechanism of the early ones. Occasionally, the central engine produces a faster than average shell, originating the late flares often observed in the *Swift* X-Ray Telescope light curves.

Our suggestion may be not the only solution of the puzzle concerning the unpredicted behavior of the X-ray and the optical light curves. Indeed, Uhm & Beloborodov (2007) and Grenet et al. (2007) recently proposed that the X-ray flux may be dominated by the reverse shock emission in slow shells. These and our proposals share the common view that the X-ray flux can be due to a component different from what produces the optical. The difference is that in our model the late prompt and real afterglow emissions are completely decoupled, while in the reverse shock scenario the two emission processes are linked. Furthermore, in the reverse shock scenario, one has to assume a somewhat ad hoc time profile of the Γ -factor to explain the flat-steep X-ray transition (Uhm & Beloborodov 2007), which is not a simple (unbroken) power law as in our case.

Finally, there are some features that our model can predict. Observationally, we should have the three cases mentioned above: both the optical and the X-rays are late prompt emission; both are real afterglow emission; X-rays and optical are “decoupled,” with the X-ray due to late prompt and the optical due to real afterglow emission, respectively. One obvious way to check these possibilities is through the construction of the simultaneous spectral energy distribution (SED), which can confirm whether the X-ray and the IR-optical fluxes belong to the same component. The unknown extinction due to the host galaxy material may complicate this test, but having enough photometric data, especially in the infrared, may result in a good determination of the extinction and thus a good estimate of the extrapolation of the IR-optical spectrum into the X-ray range. The SED so obtained may clearly show that the IR-optical and X-ray emission belong (or not) to two different components.

Another test concerns the total kinetic energy of the fireball after its radiative phase, using the radio data, as done, for example, for GRB 970508 by Frail et al. (2000). Should the derived energetics be smaller than that required by the refreshed shock scenario, one could exclude this possibility and instead favor our scenario.

In cases in which the late prompt emission ends, the underlying real afterglow emission can be revealed. In the light curve, this should appear as a steep-flat transition at late times (not to be confused with the usual steep-flat-steep X-ray decay). This can also be confirmed by the corresponding SEDs.

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