“LATE PROMPT” EMISSION IN GAMMA RAY BURSTS?

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ABSTRACT

The flat decay phase in the first \(10^2–10^4\) seconds of the X-ray light curve of Gamma Ray Bursts (GRBs) has not yet found a convincing explanation. The fact that the optical and X-ray lightcurves are often different, with breaks at different times, makes contrived 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 \(\Gamma\). 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 \(\Gamma\) of the late shells is larger than \(1/\theta_j\), where \(\theta_j\) is the jet opening angle, we see only a portion of the emitting surface. Eventually, \(\Gamma\) 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 to the time at which the plateau ends. After the steeply decaying phase which 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 — X-rays: general — radiation mechanisms: general

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 thought in the pre–Swift era. After a steep decline of the flux \(F(t) \propto t^{-\alpha_j}\), with \(\alpha_j \sim 3–5\); 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 \(F(t) \propto t^{-\alpha_3}\), with \(\alpha_3 \sim 0.2–0.8\), 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. 2005), i.e. in a similar way as 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 (2006) 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: i) energization of the forward shock by the arrival of shells being produced late (with large \(\Gamma_s\)), or just after the prompt phase (with small \(\Gamma_s\)); ii) changing microphysical parameters, assuming that the efficiency of the forward shock to produce radiation increases with time: iii) off–axis jets, whose prompt and early afterglow radiation is not fully beamed towards the observer. Note that the spectral slope does not change across the temporal break from the shallow decay phase to the normal

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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 $\Gamma$-factors (changing erratically) and energy, due to e.g. internal shocks (Rees & Meszaros, 1994) or interactions with the funnel of the progenitor star (Thompson 2006; Thompson Meszaros & Rees 2006), or some form of magnetic reconnection (e.g. Spruit, Daigne & Drenkhahn 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 $\Gamma$ 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 $\Gamma$ implies less variability during the late prompt. Furthermore, if $\Gamma$ is decreasing with time, a new effect appears. In fact, when $\Delta \alpha$ is still negative during the late prompt phase ($t_\alpha$), is of the order of

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

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 $\eta$ for the dissipation process leading to the radiation produced in the plateau phase. After $t_d$, when we see the entire emitting surface, the jet kinetic power per unit solid angle $L_{\text{kin}} = \Gamma M c^2 \sim 2 L_X/((\theta_j^2) \eta)$ and then

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

which approximately gives $\dot{M} \propto t^{-1}$, 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 at most comparable with what can be estimated for the ejecta of the early prompt. This is because, although the $\Gamma$-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 $\sim 10$ smaller than the early prompt. Therefore, if $\eta$ 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 due both 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 wind–like profile. Calling $t_i$ the time (after the trigger) at which a late shell is created, and $t_d$ the deceleration time, we have that at the observed time $t$ the front shock and the $i$-th late shell are at the distances $R_s$ and $R_i$, respectively, given by:

$$R_s = ct_i^2 = c\Gamma_0^2 \left( \frac{t_d}{t_i} \right)^{-1/2} = c\Gamma_0^2 (tt_d)^{1/2}$$

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

where $\Gamma_0$ is the initial Lorentz factor of the early shells. Late shells are assumed not to decelerate until they catch up the front shock. Equating the two above radii we have that the $i$th shell reaches the front shock at the time $t_c$:

$$t_c \sim \frac{\Gamma_i^4}{\Gamma_0^4} t_d; \quad \text{if} \quad t_c \gg t_i$$

For $t_d = 100$ s, $t_c$ ranges from 1600 s ($\Gamma_0/\Gamma_i = 2$) to $t_c = 10^6$ ($\Gamma_0/\Gamma_i = 10$). 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.

We use the notation $Q_x = 10^x Q$, in cgs units.
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–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 REM 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 seen in the optical, we need another component to explain the X–ray flux. We also conclude that: i) the real afterglow X–ray component is much weaker than thought before; ii) the X–ray band is likely not the band where most of the afterglow energy is, and iii) the total energetics of the real afterglow is much smaller than thought before.

A weak afterglow can result if the microphysical parameters \( \epsilon_e, \epsilon_B \), 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 \( \gamma_p \) of the prompt and the plateau phase are broad, but a slight narrowing around a value \( \gamma_p \sim 1 \) for the plateau is visible. We propose that this is not due to the prompt/afterglow transition, but it is instead associated to the transition between the early prompt phase, characterized by large \( \Gamma \)–factors changing erratically, and the late prompt phase characterized by smaller \( \Gamma \) decreasing monotonically.

Note also that the pre–Swift observations of the X–ray “afterglow” should be re–interpreted: in many cases, what 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 to 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 time Doppler contraction, 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 here proposed allows to explain some GRB properties which 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 which 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 both in the X–ray and in the optical bands. Focusing to 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 Fig. 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 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 which largely overtake the energy of the first shells, which have contributed to the early prompt emission. Alternatively, in the increasing \( \epsilon_e, \epsilon_B \) 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 need 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 on how the central engine works. The following ideas should then be considered 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 which 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 fall–back 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/XRT light curves.

Our suggestion may be not the unique solution of the puzzle concerning the unpredicted behavior of the X–ray and the optical light curves. Indeed, Uhm & Beloborodov (2007) and Grenet, Daigne & Mochkovitch (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 and 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 or not if 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 e.g. for GRB 970508 by Frail, Waxman & Kulkarni (2000). Should the derived energetics be smaller than what 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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REFERENCES

Fig. 1.— Schematic illustration of the different components contributing to the X–ray and optical light curves, as labelled. 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). $\Gamma_{LP}$ and $\Gamma_{FS}$ indicate the $\Gamma$ of the late shells and the forward shocks, respectively.