The flat decay phase in the early X-ray afterglows of Swift GRBs(*)

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Summary. — Many *Swift* GRBs show an early phase of shallow decay in their X-ray afterglows, lasting from $t \sim 10^{2.5}$ s to $\sim 10^4$ s after the GRB, where the flux decays as $\sim t^{-0.2} - t^{-0.8}$. This is perhaps the most mysterious of the new features discovered by *Swift* in the early X-ray afterglow, since it is still not clear what causes it. I discuss different possible explanations for this surprising new discovery, as well as their potential implications for the gamma-ray efficiency, the afterglow kinetic energy, and perhaps even for the physics of collisionless relativistic shocks.

PACS `98.70.Rz` – γ-ray sources; γ-ray bursts.

1. – Introduction

Before the launch of *Swift*, the monitoring of GRB afterglows typically started at least several hours after the GRB. The extrapolation back in time of the observed X-ray afterglow power law flux decay usually gave a flux similar to that of the prompt emission around the end of the GRB. Therefore, most people believed that *Swift* would detect a simple single power law flux decay all the way from the end of the prompt emission up to the late times that were observed before *Swift*. It had even been hoped that this would significantly improve the constraints on the external density profile around the GRB.

After the launch of *Swift*, however, a new and surprising picture soon emerged, where the early X-ray afterglow showed several interesting and unexpected features [1]. These included mainly i) an initial rapid decay phase where $F_\nu \propto t^{-\alpha}$ with $3 \lesssim \alpha_1 \lesssim 5$ lasting from the end of the prompt emission up to $\sim 10^{2.5}$ s, ii) a subsequent flat decay phase where $0.2 \lesssim \alpha_2 \lesssim 0.8$, lasting up to $\sim 10^4$ s (followed by the familiar pre-*Swift* power law decay with $1 \lesssim \alpha_3 \lesssim 1.5$), and iii) X-ray flares, which appear to be overlaid on top of the

underlying power law decay in stages i) and ii). The initial rapid decay stage appears to be a smooth extension of the prompt emission [2], and is therefore most likely the tail of the prompt GRB, probably due to emission from large angles relative to our line of sight [3]. The X-ray flares appear to be a distinct emission component, as suggested by their generally different spectrum compared to the underlying power law component, and by the fact that the flux after a flare is usually the continuation of the same underlying power law component from before the flare [4,5]. In many cases these flares show sharp large amplitude flux variation on time scales $\Delta t \ll t$ (see, *e.g.* [6]), which are very hard to produce by the external shock, and suggest a sporadic late time activity of the central source.

The flat (or shallow) decay phase, stage ii), and the initial rapid decay phase, stage i), appear to arise from two physically distinct emission regions. This is supported by a change in the spectral index that is observed in some of the transitions between these two stages [1]. Furthermore, the flat decay phase eventually smoothly steepens into the familiar pre-*Swift* flux decay, which is well established to be afterglow emission from the forward shock, strongly suggesting[1] that the flat decay phase is similarly afterglow emission from the forward shock. This is also supported by the fact that there is no evidence for a change in the spectral index across this break [1]. Nevertheless, it is still not clear what causes this shallow decay phase. Below I briefly describe different possibilities and mention some of their possible implications.

2. – Energy injection into the afterglow shock

Perhaps the simplest explanation for the flat decay phase is gradual and continuous energy injection into the afterglow (forward) shock [1, 7, 8]. This can take place in two main forms [1]: 1) a smooth distribution of ejected mass as a function of its Lorentz factor, $M(> \Gamma) \propto \Gamma^{-s}$, and its corresponding energy, $E(> \Gamma) \propto \Gamma^{-a}$ where $a = s - 1$. In this picture Γ increases with radius R[2]. Material with Lorentz factor Γ catches up with the forward shock when the Lorentz factor of the forward shock, Γ_f, drops slightly below Γ [9-11], resulting in a smooth and gradual energy injection into the afterglow shock. 2) An alternative scenario for the energy injection is that the central source remains active for a long time [12-16], where the ejected outflow (or wind) has a Lorentz factor, $\Gamma_i \gg \Gamma_f$. This leads to a highly relativistic reverse shock (with a Lorentz factor $\Gamma_r \sim \Gamma_i/2\Gamma_f \gg 1$), while in scenario 1) the reverse shock is only mildly relativistic, thus resulting in a different emission from the reverse shock which may potentially be used in order to distinguish between these scenarios.

In scenario 1) the observed shallow decay phases typically imply $1 \lesssim a \lesssim 2.5$ for a uniform external density and $a \gtrsim 5$ for a wind-like external density [1, 17] (which drops as the inverse square of the distance from the source), while most of the energy in the relativistic outflow is in material with $\Gamma \sim 15$–50 for a uniform external density and $\Gamma \sim 10$–20 for a wind-like environment (see fig. 1). In scenario 2) the observations typically imply an isotropic equivalent late time energy deposition rate into the outflow

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[1] The reason for this is that obtaining a smooth transition where the flux decay *steepens* between two distinct emission regions requires fine tuning, and therefore is highly unlikely to happen for practically every flat decay phase, as is implied by observations.

[2] This can naturally occur if toward the end of the prompt GRB the Lorentz factor of the outflow that is being ejected decreases with time. Even if Γ does not monotonically increase with R initially, but there is still some distribution in the initial Lorentz factor, such an ordering (where Γ increases with R) will naturally be achieved as the result of internal shocks.
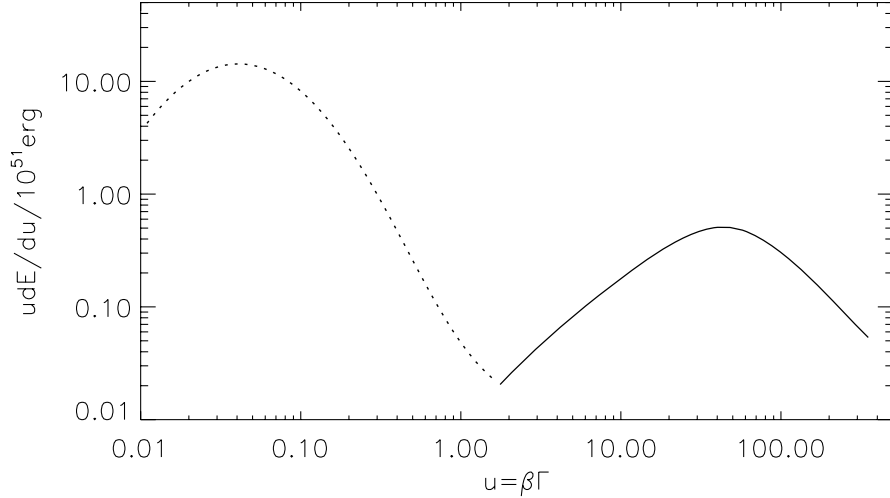
Fig. 1. – Schematic figure showing the distribution of energy E as a function of four velocity $u \equiv \Gamma\beta = (\Gamma^2 - 1)^{1/2}$ ($\mathrm{d}E/\mathrm{d}\ln u$, in units of 10^{51} erg), that is implied if the flat decay phase is due to type (1) energy injection (from [17]). It has one relativistic component (solid line) with total energy $\sim 10^{51}$ erg and peak at $u \sim 30$–50 that produces the GRB ($u \gtrsim 10^2$) and the afterglow radiations. The power law index above the peak for this component is well constrained by the X-ray data (the shallow part of the light curve) and is $\mathrm{d}E/\mathrm{d}\ln u \propto u^{-a}$ with $1 \lesssim a \lesssim 2.5$ for a uniform external medium. The slope below the peak is not well constrained (either than being positive) and is taken to be 1. The second component (dashed curve) shows schematically the kinetic energy in non-relativistic ejecta in the supernova accompanying the GRB, which peaks at a typical velocity around $\sim 10^4\,\mathrm{km\,s^{-1}}$, and has an energy of the order of $\sim 10^{52}$ erg.

of $L_{\mathrm{iso}} \propto t_{\mathrm{lab}}^{q}$ with $q \sim -0.5$, where t_{lab} is the lab frame time [1]. The latter may, at least in some cases, be consistent with the expectations for the spin-down luminosity of a newly born millisecond magnetar [18, 12] where q varies smoothly from $q \approx 0$ at early times (before considerable spin-down has occurred) to $q \approx -2$ at late times.

3. – Viewing angles slightly outside the emitting region

An interesting alternative explanation for the flat decay phase is a viewing angle slightly outside the region of prominent afterglow emission [19]. In this interpretation the shallow decay phase is the combination of the decaying tail of the prompt emission (*e.g.* [3]) and the gradual delayed onset of the afterglow for such off-beam viewing angles (*e.g.* [20]), as is illustrated in fig. 2. The fact that such a flat decay phase is observed in a large fraction of *Swift* X-ray afterglows, in most of which the prompt γ-ray emission is relatively bright, suggests in this picture that many observers have a very high ratio of γ-ray to kinetic (isotropic equivalent) energy at early times along their line of sight. This requires a high efficiency of the prompt γ-ray emission, of $\epsilon_\gamma \gtrsim 90\%$, under the standard assumptions of afterglow theory, as discussed in sect. **6**.
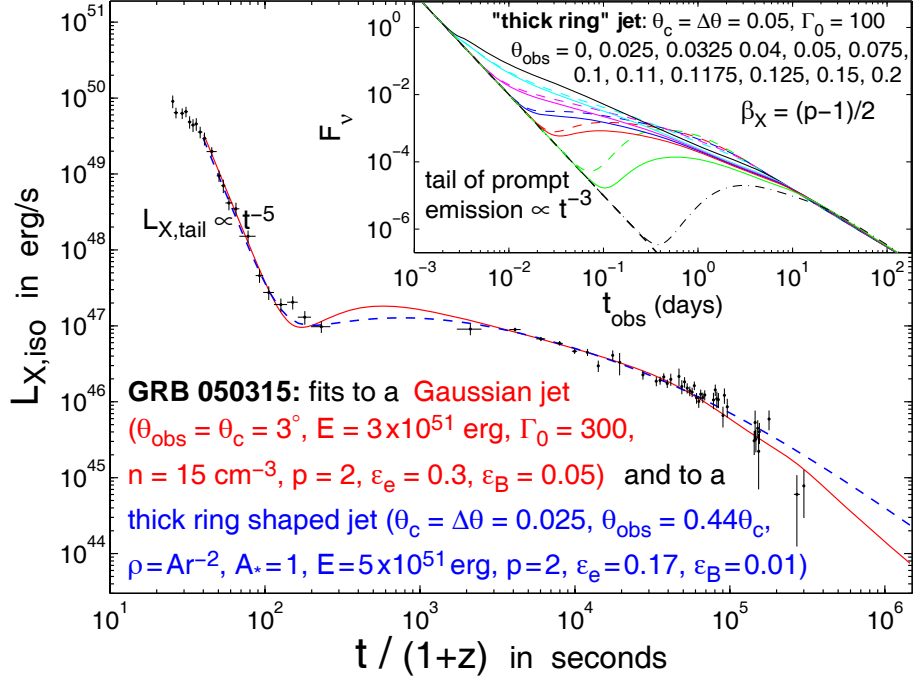
Fig. 2. – Tentative fits to the X-ray light curve of GRB 050315, for a viewing angle slightly outside the region of bright afterglow emission (from [19]). The inset demonstrates the variety of different light curve shapes that are obtained for different viewing angle, which may in principle accommodate the observed diversity. For details see [19].

4. – Two-component jet

This explanation envisions a distribution of the initial Lorentz factor as a function of direction, *i.e.* with angle within the collimated outflow, $\Gamma_0 = \Gamma_0(\theta)$. This should not be confused with the distribution in the initial Lorentz factor along the same direction, as in type (1) energy injection that was discussed in sect. **2**. The local deceleration time (at which most of the local energy is transferred to the shocked external medium) at each point in the jet depends sensitively on the local value of the initial Lorentz factor (and less sensitively on the local energy per solid angle; see, *e.g.*, eq. 12 of [21]). Therefore, the regions that contribute to the prompt γ-ray emission, which typically have an initial Lorentz factor $\Gamma_0 \gtrsim 10^2$, decelerate early on (on a time scale similar to the duration of the GRB), while regions with smaller Γ_0 decelerate and start contributing significantly to the afterglow emission only at later times.

In the simplest version of this picture there are two discrete jet components: an inner narrow jet of half-opening angle θ_n with $\Gamma_0 = \eta_n \gtrsim 10^2$, surrounded by a wider jet of half-opening angle $\theta_w > \theta_n$ with a smaller $\Gamma_0 = \eta_w \sim 10\text{--}30$. Theoretical motivation for such a jet structure has been found both in the context of the cocoon in the collapsar model [22] and in the context of a hydromagnetically driven neutron-rich jet [23]. It was invoked by [24] as a possible way to alleviate the pre-*Swift* constraints on the γ-ray emission efficiency, ϵ_γ. However, *Swift* observations show that while it may produce the observed flat decay phase (as is illustrated in fig. 3), it still requires a very high ϵ_γ, under standard assumptions [25].
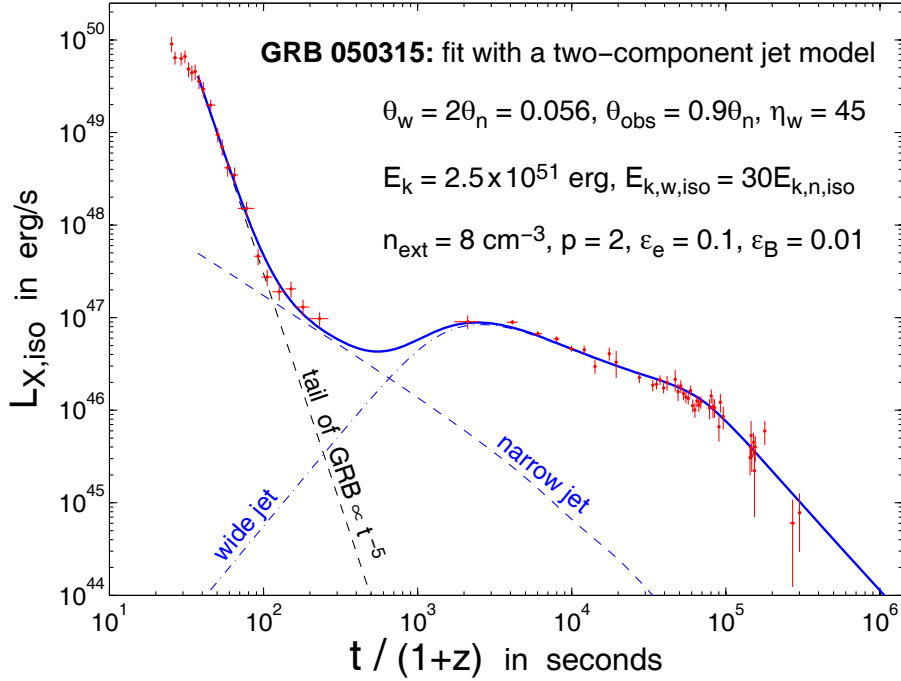
Fig. 3. – Tentative fit to the X-ray light curve of GRB 050315, for a two-component jet (from [25]). For details see the text and/or [25].

5. – Initial increase with time of the afterglow efficiency

All previous explanations relied on an increase with time in the typical afterglow isotropic equivalent kinetic energy, $E_{k,iso}$, within the observed region, either through an increase in $E_{k,iso}$ along the line of sight (sect. **2**) or as other regions start to contribute significantly to the observed flux (sects. **3**,**4**). In this explanation, however, $E_{k,iso}$ in the observed region remains constant from very early on (around the deceleration time), but the efficiency of the X-ray afterglow emission, ϵ_X, initially increases with time [25].

It is natural to define $\epsilon_X(t) \equiv t L_{X,iso}/E_{k,iso}$ where $L_{X,iso}$ is the afterglow isotropic equivalent X-ray luminosity. The ratio $\epsilon_X(t)E_{k,iso}(t)/tF_X(t)$ (where F_X is the X-ray afterglow flux) depends only on the redshift, and is constant in time (see eq. 15 of [25]). In the flat decay phase $F_X \propto t^{-\alpha}$ with $\alpha_2 < 1$, so that $tF_X(t)$ increases with time, and therefore $\epsilon_X(t)E_{k,iso}(t)$ must similarly increase with time. In other explanations this was attributed to an increase with time of $E_{k,iso}(t)$ (where $\epsilon_X(t)$ slowly decreases with time), while in the current explanation $E_{k,iso}$ remains constant, while ϵ_X initially increases with time, thus causing the shallow decay phase. This might be causes by a value of $p < 2$ for the power law index of the electron energy distribution [25]. In this case, however, radiative losses might become important (which would steepen the flux decay) and this option is often inconsistent with the measured spectral slope in the X-rays.

A more interesting way for ϵ_X to increase with time is due to an increase with time in one or more of the following shock microphysical parameters: the fraction of the internal energy in relativistic electrons, ϵ_e, or in magnetic fields, ϵ_B, or the fraction ξ_e of the

electrons that are accelerated to a relativistic power-law distribution of energies. (for more details see [25]). In this scenario, the shock microphysical parameters eventually saturate at some asymptotic values, bringing the flat decay phase to an end. If this is indeed the cause for the shallow decay phase, then the observations of this phase can potentially be used in order to constrain the physics of collisionless relativistic shocks.

6. – Implications for the gamma-ray efficiency and for the jet energy

Pre-*Swift* studies [26-28] found that $E_{\rm k,iso}$ at late times (typically evaluated at $t_* = 10\,{\rm h}$), $E_{\rm k,iso}(t_*)$, is comparable to the isotropic equivalent energy output in γ-rays, $E_{\gamma,\rm iso}$, *i.e.* that typically $\kappa \equiv E_{\gamma,\rm iso}/E_{\rm k,iso}(t_*) \sim 1$. The γ-ray efficiency is given by $\epsilon_\gamma = E_{\gamma,\rm iso}/(E_{\gamma,\rm iso} + E_{\rm k,iso,0})$, where $E_{\rm k,iso,0}$ is the initial value of $E_{\rm k,iso}$ corresponding to material with a sufficiently large initial Lorentz factor ($\Gamma_0 \gtrsim 10^2$) that could have contributed to the γ-ray emission. This implies a simple relation, $\epsilon_\gamma/(1 - \epsilon_\gamma) = \kappa f$, where $f \equiv E_{\rm k,iso}(t_*)/E_{\rm k,iso,0}$ can be estimated from the early afterglow light curve [25].

Interpreting the shallow decay phase in the early X-ray afterglow as energy injection [1, 8, 7, 17] typically implies $f \gtrsim 10$ and $\epsilon_\gamma \gtrsim 0.9$ [1, 19, 25]. This is a very high efficiency for any reasonable model for the prompt emission, and in particular for the popular internal shocks model. If the shallow decay phase is not caused by energy injection, but is instead due to an increase with time in the afterglow efficiency, then $f \sim 1$ and typically $\epsilon_\gamma \sim 0.5$ [25]. This is a more reasonable efficiency, but still rather high for internal shocks. If, in addition, $E_{\rm k,iso}(10\,{\rm h})$ had been underestimated, *e.g.*, due to the assumption that $\xi_e = 1$, then[3] $\kappa \sim \xi_e$ and $\xi_e \sim 0.1$ would lead to $\kappa \sim 0.1$ and $\epsilon_\gamma \sim 0.1$.

The internal shocks model can reasonably accommodate γ-ray efficiencies of $\epsilon_\gamma \lesssim 0.1$, which in turn imply $\kappa \lesssim 0.1$. Since the true (beaming-corrected) γ-ray energy output, $E_\gamma = f_b E_{\gamma,\rm iso}$ (where $f_b \approx \theta_0^2/2$ and θ_0 is the half-opening angle of the uniform jet), is clustered around 10^{51} erg [30, 31], this implies $E_k(t_*) = f_b E_{\rm k,iso}(t_*) = \kappa^{-1} E_\gamma \gtrsim 10^{52}$ erg for a uniform jet. For a structured jet with equal energy per decade in the angle θ from the jet symmetry axis ($\mathrm{d}E/\mathrm{d}\Omega \propto \theta^{-2}$) in the wings (between some inner core angle θ_c and outer edge $\theta_{\max}$), the true energy in the jet is larger by a factor of $1 + 2\ln(\theta_{\max}/\theta_c) \sim 10$, which implies $E_k(t_*) \gtrsim 10^{53}$ erg in order to achieve $\epsilon_\gamma \lesssim 0.1$. Such energies are comparable (for a uniform jet) or even higher (for the latter structured jet) than the estimated kinetic energy of the Type Ic supernova (or hypernova) that accompanies long-soft GRBs. This is very interesting for the total energy budget of the explosion.

7. – Conclusions

The flat (or shallow) decay phase is arguably the most striking of the new features found by *Swift* in the early X-ray emission of GRBs. Nevertheless, it is still not clear what causes it. There are many possible explanations, which include energy injection into the afterglow shock (sect. **2**), viewing angle effects (sect. **3**), a two component jet (sect. **4**), or an initial increase with time in the efficiency of the afterglow emission (sect. **5**). Good monitoring of the early afterglow emission over a wide range in frequency, might help to distinguish between the different explanations. It is not obvious, however, whether any

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(^{3}) In ref. [29] a degeneracy has been pointed out where the same afterglow observations are obtained under the substitution $(E, n) \to (E, n)/\xi_e$ and $(\epsilon_e, \epsilon_B) \to \xi_e(\epsilon_e, \epsilon_B)$ for a value of ξ_e in the range $m_e/m_p \leq \xi_e \leq 1$, instead of the usual assumption of $\xi_e = 1$.

of the explanations that have been mentioned here is indeed the dominant cause for the shallow decay phase. Evidence is accumulating that the steepening in the flux decay at the end of the shallow decay phase is chromatic [32]—it is observed in the X-rays but not in the optical. This is in contradiction with the expectations of all explanations that have been put forth so far for the flat decay phase, where the steepening at its end is expected to be largely achromatic. There is definitely still a lot of work ahead of us in trying to understand the origin of these fascinating new observations in the *Swift* era.

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