

# Some Recent Peculiarities of the Early Afterglow

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**Abstract.** We consider some recent developments in GRB/afterglow observations: (i) the appearance of a very hard prompt component in GRB 941017, and (ii) variability in the early afterglow light curves of GRB 021004 and GRB 030329. We show that these observations fit nicely within the internal-external shocks model. The observed variability indicates that the activity of the inner engine is more complicated than was thought earlier and that it involves patchy shells and refreshed shocks. We refute the claims of Berger et al. and of Sheth et al. that the radio and mm observations of GRB 030329 are inconsistent with refreshed shocks.

## Introduction

The early afterglow and the GRB/afterglow transition are among the unexplored regimes of GRBs. A great progress on this front was achieved during the last year when, following fast HETE II identifications, two afterglows (GRBs 021004, 030329) were followed from very early on showing remarkable variability and rich structure. Also, somewhat unexpectedly, a search within the BATSE/EGRET archives revealed a new very hard long lasting ( $\sim 200$  s) component of GRB 941017. This is most likely a manifestation of the early afterglow and of the GRB/afterglow transition. We discuss these developments and their implication within the internal-external shocks model.

## The Prompt High Energy Emission from GRB 941017 as a GRB/afterglow transition

Recently, González et al. [1] discovered a high energy tail that extended up to 200 MeV in the combined BATSE and EGRET data of GRB 941017. The tail had a hard spectral slope ( $F_\nu \propto \nu^0$ ) up to 200 MeV. It appeared  $\sim 10$ -20 s after the beginning of the burst and displayed a roughly constant flux while the lower energy component decayed. At late times ( $\sim 150$  s after the trigger) the very high energy ( $\sim 10$ -200 MeV) tail had a luminosity  $\sim 50$  times higher than the “main”  $\gamma$ -ray energy band ( $\sim 30$  keV-2 MeV).

Granot & Guetta [2] were the first to suggest that we see here another manifestation of the very early afterglow. Sari [3] has shown that for long bursts the external shocks (and hence the afterglow) begin  $\sim R/c\Gamma^2$  after the beginning of the burst while the internal shocks are still going on and hence the burst is still active. This behavior was seen in the transition from the harder initial burst to the softer early afterglow [4, 5, 6]. It was also seen in the prompt optical flash of GRB 990123 where the lower

(optical) energy component did not trace the  $\sim$ MeV  $\gamma$ -rays and a pronounced hard to soft evolution was seen in the  $\gamma$ -ray signal.

The very high energy of this emission suggests that it is inverse Compton. There are two relevant emitting regions in the early afterglow: the forward shock and the reverse shock. With typical parameters [7] the energy of the synchrotron photons and the electrons' Lorentz factor in the forward and reverse shocks are:

$$\begin{aligned} v_{\text{synch,F}} &\approx 0.1 \text{ MeV } (\Gamma/300)^4 ; & \gamma_{e,\text{F}} &\approx 10^4 (\Gamma/300) \\ v_{\text{synch,R}} &\approx 1 \text{ eV } (\Gamma/300)^2 ; & \gamma_{e,\text{R}} &\approx 300 \end{aligned}$$

There are four possible combinations of seed photons and scattering electrons:

	Rev. shock electrons	For. shock electrons
Rev. shock photons	$\sim 0.1 \text{ MeV } (\Gamma/300)^2$	$\sim 100 \text{ MeV } (\Gamma/300)^3$
For. shock photons	$\sim 10 \text{ GeV } (\Gamma/300)^4$	$\sim 10 \text{ TeV } (\Gamma/300)^5$ (within Klein Nishina)

While these approximate results are very sensitive to  $\Gamma$ , they indicate that inverse Compton scattering of the reverse shock photons on the forward shock electrons yields the right energy range. The detailed calculations of Pe'er & Waxman [8] confirm these naive estimates. The main problem, however, is not to explain the location of the spectral peak but to explain the spectral slope ( $F_\nu \propto \nu^0$ ) and the temporal slope ( $F_\nu \propto t^0$ ). Pe'er & Waxman [8] reproduce the spectral slope by requiring that the synchrotron self absorption frequency of the reverse shock emission would be high enough to effect the observed spectrum. Granot & Guetta [2] reproduce both the temporal and spectral behaviors by considering a slightly different scenario where the high energy component is produced by Synchrotron self Compton within the reverse shock. They require a slightly higher external density with a somewhat unusual profile,  $\propto R^{-1}$ , for a uniform ejecta shell (which may explain the rareness of the event). In both models the high energy component is a clear manifestation of the onset of the afterglow and the GRB/afterglow transition.

## Afterglow Light curve variability

**Theory:** The different scenarios that lead to afterglow temporal variability can be distinguished according to their characteristic features. Density variations produce only weak fluctuations above the cooling frequency,  $\nu_c$ , and cannot produce sharp changes in the light curve. Energy variations produce variability both above and below  $\nu_c$ , and can arise either due to refreshed shocks or due to a patchy shell structure. These two mechanisms produce very different light curves. While the former produce a step-wise increase in the light curve, the later produces random fluctuations with a decreasing amplitude.

Rees & Mészáros [9], Kumar & Piran [10] and Sari & Mészáros [11] suggested that slow shells take over the slowing down matter behind the afterglow shock and produce *refreshed shocks*. Slow shells with  $\Gamma_s$  emitted from the source right after the fast ejecta, catch up and collide with the slowing down ejecta at an observer time  $t \sim 0.25(\Gamma_s/10)^{-8/3}(E_{\text{iso},52}/n_0)^{1/3}$  days (where  $E_{\text{iso},52}$  is the isotropic kinetic energy

in units of  $10^{52}$  ergs and  $n_0$  is the external density in  $\text{cm}^{-3}$ ) when the ejecta's Lorentz factor drops slightly below  $\Gamma_s$ . The clearest feature of refreshed shocks is a monotonous increase in the overall energy. Therefore the observed flux can only increase (relative to the expected decay). The light curve has a step wise form with each step produced by the arrival of a single shell. This step wise structure is seen both above and below the cooling frequency with a similar amplitude. Each step (in the optical light curve) should be accompanied by a flare in low frequencies that is produced by the reverse shock which propagates back into the slow shell [10, 11]. The time scale,  $\Delta t$  of the steps and the corresponding flares depends on their timing relative to the jet break. Before the jet break the refreshed shocks are "locally" spherically symmetric and therefore the angular time imposes  $\Delta t \sim t$  [10]. The intensity of the reverse shock flare in this regime is calculated in [10], and the decay after the peak is  $\propto t^{-2}$  [7]. In the post-break case the cold slow shells may not expand sideways (if cold enough). Then they keep their original angular size,  $\theta_j$ , which is smaller than  $\Gamma_s^{-1}$ . In this case  $\Delta t \approx t_j < t$ , where  $t_j$  is the jet break time [12] and the transition is fast. A reverse shock flare is expected in this case as well. However, its frequency, intensity and temporal decay (which is expected to be steeper than in the spherical case) are much harder to calculate.

Kumar & Piran [13] suggested, in the *Patchy shell model*, that the shells have an intrinsic angular structure. As the blast wave decelerates the angular size of the observed region ( $\sim 1/\Gamma$ ) increases. The effective (average) energy of the observed region and hence the observed flux, relative to the expected decay, varies with time depending on the angular structure. The variability time scale is  $\Delta t \sim t$  [14]. The averaging over a larger and larger random structure leads to a decay of the envelope as  $t^{-3/8}$  [14, 15]. An important feature of this scenario is the break of the axial-symmetry and therefore the production of a linear polarization. The variation of the polarization, both in degree and in angle, are correlated with the light curve variations [14, 16]. The variability will be observed both above and below the cooling frequency  $\nu_c$  with a similar amplitude.

Wang & Loeb [17], Lazzati et al. [18] and Nakar et al. [15] considered *External density variations*. Such variations may result from ISM turbulence or from a variable pre-burst stellar wind. Wang & Loeb [17] analyzed the light curve resulting from mild density fluctuations due to ISM turbulence. They show that these density fluctuations can produce short time scale ( $\Delta t < 0.1t$ ) and low amplitude ( $\sim 10\%$ ) fluctuations in the light curve. Lazzati et al.[18], Nakar et al. [15] and Nakar & Piran [19] considered large amplitude spherical density fluctuations. A basic feature of the resulting light curve that distinguishes it from energy variations is that in the former the light curve is different above and below the cooling frequency,  $\nu_c$ . Density variations produce only weak fluctuations above  $\nu_c$ . The amplitude of the fluctuations above  $\nu_c$  is at most tens of percents and it is much smaller than the amplitude of the fluctuations below  $\nu_c$  [19].

A second feature of density fluctuations is their inability to produce a sharp variation (either increase or decrease) in the light curve [20]. First, we note that because of angular spreading, spherical density drops cannot produce decays sharper than  $t^{-2.6}$  [19, 21] and even this decay is reached very slowly. More interesting is the fact that even a sharp density enhancement cannot produce a steep increase in the light curve. The earlier calculations [15, 18, 19] assumes that the ejecta can be described by a Blandford-McKee solution whose density profile varies instantaneously according to the external density.

These calculations do not account, however, for the reverse shock resulting from density enhancement and its effect on the blast-wave. Thus the above models are limited to slowly varying and low contrast density profiles. Now, the observed flux depends on the external density,  $n$ , roughly as  $n^{1/2}$ . Thus, a large contrast is needed to produce a significant re-brightening. Such a large contrast will, however, produce a strong reverse shock which will sharply decrease the Lorentz factor of the emitting matter behind the shock,  $\Gamma_{sh}$ , causing a sharp drop in the emission below  $v_c$  and a long delay in the arrival time of the emitted photons (the observer time is  $\propto \Gamma_{sh}^{-2}$ ). Both factors combine to suppresses the flux and to set a strong limit on the steepness of the re-brightening events caused by density variations. Note that while non spherical density fluctuations may lead to a steeper decline they usually do not lead to a steeper increase in the flux.

**Implications:** The early afterglow of **GRB 021004** showed clear deviations from a smooth power law decay, lasting from 0.04 days to 3 days. The fluctuations in the light curve were accompanied by fluctuations both in the degree and in the angle of the polarization ([14] and references therein).

The steep decays after each bump imply that the variations do not result from re-freshed shocks. Thus, variable external density variations [15, 18, 22] and the patchy shell model [14, 15] were considered as possible explanations. Unfortunately, the X-ray observations are not detailed enough to clearly distinguish between density and energy variations (although the former are favored by [22]). However, the sharp decays cannot be produced by “locally” spherical density variations [19]. Furthermore, the first bump requires, using the instantaneous Blandford-McKee approximation, an increase in the external density by a factor of  $\sim 10$  over  $\Delta R/R \approx 0.05$  [18, 19]. Such a density contrast produces a mildly relativistic reverse shock which reduce  $\Gamma_{sh}$  by a factor of  $\approx 2$ , making the approximation inconsistent. Preliminary results [20] of detailed numerical simulations (including both hydrodynamics and synchrotron radiation) suggest that this bump cannot be produced by density enhancement (due to the suppressed forward shock emission, caused by the reverse shock). These results leave the patchy shell as the only viable explanation. Indeed, Nakar & Oren [14] show that patchy shell can reproduce the light curve (including the sharp rise and steep decay of the first bump). They show that angular energy profiles which produce the observed light curve produce also a polarization curve that fits the observed polarization. We conclude that angular energy fluctuations are the dominant process that produce the observed fluctuations in GRB 021004.

In addition to the remarkable supernova signature, the optical afterglow **GRB 030329** has shown also a unique variability ([12] and references therein). Several step-wise bumps, at  $t = 1.5, 2.6, 3.3$  and  $5.3$  days, are seen after the jet break at  $t_j \approx 0.5$  days. The first bump was the largest and best monitored, but even with the less dense monitoring of the later bumps the step-wise profile (where after each bump the original decay slope is resumed) is clear. All the bumps had a short rise time  $\Delta t \approx 0.4-0.8 \text{ d} < t$ . The step-wise profile seems like a clear signature of post-break refreshed shocks [12], where  $\Delta t \approx t_j < t$  because the later slower shells did not expand sideways before colliding with the faster earlier ejecta. Moreover, the energy injected in these shocks is 10 times the energy in the original blast-wave. This late (or rather slow) energy injection explains an additional peculiarity of this GRB: the low energy output in  $\gamma$ -rays and in the early X-ray afterglow.

Berger et al. [23] suggested that the first bump and the energy deficiency can be

explained by a two component jet: A slow and energetic component with a wide half-opening angle ( $17^\circ$ ) dominates the afterglow after 1.5 days, and a fast component with a narrow half-opening angle ( $5^\circ$ ) dominates the afterglow before 1.5 days. The slow component is observed only after 1.5 days  $\approx t_{\text{dec}} \approx 0.5(\Gamma_s/10)^{-8/3}(E_{\text{iso},52}/n_0)^{1/3}$  days, since only at this time its reverse shock consumes the slow shell. However, this model, which received a great publicity, predicts that the rise time,  $\Delta t$ , of the first bump should be of the same order as the observed time,  $t_{\text{dec}}$ . Furthermore, it predicts a smooth light curve after the first bump. Both predictions are contradicted by the observations.

Millimeter observations of GRB 030329 [24] show that at 100 & 250 GHz the flux is rather constant during the first week. Most surprising are two measurements at 100 GHz, one before the first bump (0.6-1 d) and one after (1.7-1.9 d), which show a constant flux. Sheth et al. [24] and Berger et al. [23] claim that these results support the two component jet model and reject the refreshed shocks model due to the lack of radio flares. However this analysis overlooks the fact that the encounter of the slow component in the two-components jet model with the external matter produces a reverse shock which should produce a radio flash. This flash is analogous to the optical flash produced by the deceleration of the fast component [7], and to the radio flare expected in the refreshed shocks model. The timing of this flash is  $t_{\text{dec}} = 1.5$  d and its magnitude is easily calculated. The contribution from this reverse shock at  $t_{\text{dec}} = 1.5$  d is larger by a factor of up to  $\Gamma_s^{5/3} \sim 15$  than the flux from the forward shock. Thus a very bright and fast fading millimeter flash is expected in the two component jet model. A more detailed calculation (using [11] and the parameters of the wide jet presented in [23]) shows that both  $v_a$  and  $v_m$  of the reverse shock at  $t_{\text{dec}}$  are around 100-200 GHz and that the flux at  $v_m$  is  $\sim 500$  mJy which is an order of magnitude larger than the expected flux from the forward shock and than the observed fluxes at 100 & 250 GHz ( $\sim 50$  mJy) at this time.

The main argument of [23] in favor of a two-components jet is the existence of a second jet break in the radio after  $t_{j,2} \sim 10$  d. However, even this argument is not strongly supported by the data. According to this model the flux below  $v_m$  should rise as  $t^{1/2}$  before  $t_{j,2}$  and decay as  $t^{-1/3}$  after  $t_{j,2}$ . However, the data of [24] contradict this prediction. At 100 & 250 GHz the flux is constant before the passage of  $v_m$  and the decay after this passage (at  $t = 6$  &  $8$  d  $< t_{j,2}$ , respectively) is steeper than  $t^{-1.7}$  in both bands. This looks like a clear signature of a post break behavior in the radio at  $t > 1$  d. Now the radio observations at lower frequencies ( $\leq 22$  GHz) do not conform with the simple post-break model ( $F_\nu \propto t^{-1/3}$ ). The flux at these frequencies rises with time before the passage of  $v_m$ . Interestingly enough, this radio behavior is exactly the one predicted as the post break radio behavior by [25], using a 2D relativistic hydrodynamical simulations. We find the striking similarity between the radio observations and Fig. 2 of [25] as a very strong support that the broad band data are totally consistent with a single jet.

Sheth et al., [24] emphasize the fact that radio flare [10] was not detected during the first bump at  $t \sim 1.5$  days and argue that this rules out the refreshed shocks model. However, in the post-break refreshed shocks model, the radio flash is expected to be fainter and to decay faster than the radio flash in the two-components jet model (due to the lower energy and the lateral spreading of the slow shell as opposed to the more energetic and “locally” spherical wide jet). Thus, by assuming spherical symmetry, Sheth et al., [24] over estimate the expected flash in the post-break refreshed shocks

scenario. It may be that the flash was missed by the sparse measurements due to its lower intensity and faster decay. A detailed (and highly non trivial) calculations should be done in order find out.

## Summary

With an increasing flow of new observations we discover that GRBs and afterglows are richer than what was previously thought. The simple spherical theory had to be modified, first with jets and now with additional angular structure (patchy shells) and more extended velocity structure (refreshed shocks). The simple synchrotron theory has to be modified with inverse Compton scattering. One can worry, are we adding epicycles trying to revive a wrong theory? We don't believe so. Complications and variation are common in astrophysics and are found everywhere in nature. Moreover, the three main themes that have been introduced here: patchy shells, refreshed shocks and inverse Compton, were not invoked a posteriori to explain the new observations. On the contrary, all three have been suggested long ago. It is just natural and even reassuring to discover them when better data become available.

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