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Unveiling long lasting central-engine activity with Optical-NIR afterglows

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In the standard view describing the nature of long GRB emission, the duration of the central-engine activity has been usually considered to be much shorter that the afterglow emission variability time-scales. The discussion on the nature of X-ray flares and the recent studies on pre- and post-cursor emission observed in the gamma rays unveiled the possibility that the central-engine can be characterised by a much longer activity. In this work we discuss the signatures of late-time central-engine activity from a different perspective, i.e., in the temporal and spectral variability of the optical-NIR afterglow. We will discuss these signatures of the long-lasting central-engine activity unveiled thanks to the rich multicolour light curves obtained by the GROND instrument.

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1. Introduction

During the first decade after the discovery of the first GRB afterglow, the optical emission has been considered to be characterised by quite a smooth behaviour since the observed light curves were usually well fitted with single or broken power-law decays from some hours up to weeks after the trigger [7]. This smooth evolution can be very well described by the forward-shock emission in a standard external-shock scenario (see e.g. [14]). However, already in these *early afterglow* years, some events did not follow this simple, general behaviour. Some GRBs showed more complex light curves characterised by clear deviations from a simple power-law evolution and sudden late-time optical rebrightenings like in the case of GRB 970508 [16][13][9]. Nowadays, thanks to the fast *Swift* X-Ray Telescope (XRT) afterglow localisation, rapid ground-based robotic telescopes can start to observe the GRB optical afterglow a few dozen seconds after the trigger and give a much denser photometric coverage than before. This unveils that deviations from a simple power-law evolution in the optical bands are much more common than what expected in the previous years. Among these ground-based instrument, the Gamma-Ray burst Optical Near-infrared Detector (GROND) mounted on the 2.2 m MPG/ESO telescope at La Silla observatory [6] is able to simultaneously observe the GRB optical-NIR afterglow in 7 bands (i.e, $g', r', i', z', J, H, K_s$) allowing the study the optical-NIR spectral evolution with an unprecedented resolution. Here we will exploit this multi-colour capability of GROND to study in detail the temporal and spectral evolution of some events showing prominent rebrightenings in the framework of different theoretical models.

2. Examples of optical rebrightenings observed with GROND

2.1 Light curves

In [11] we discussed the broad-band evolution of GRB 081029, a remarkable case of optical-NIR rebrightening observed by GROND (see upper left panel in Fig. 2). Its GROND light curve is characterised by an extremely sharp intense re-brightening starting 3.5 ks after the trigger and peaking at 5.9 ks. During this time the observed light curve brightens by about 1.1 magnitudes in all 7 optical-NIR bands. The light curve is well represented by the sum of a smoothly-connected broken power-law and a smoothly-connected triple power-law model as shown in the left panel of Fig. 1. In order to account for the fast rebrightening a very steep $\alpha^{\rm rise} = -8.2 \pm 0.4$[1] temporal index for the rising portion of the triple power-law is required. After the bump a shallow decay phase starts, characterised by the presence of some much less intense wiggles, lasting until ~ 20 ks when an achromatic steepening occurs (see [11] for a detailed discussion on the light-curve fitting).

Five years after the GROND first light we are now allowed to assert that the extreme behaviour observed in GRB 081029 is not unique. In Fig. 2 we show 4 examples of prominent rebrightening observed with GROND. In this section we focus in particular on GRB 100621A. This GRB represents the most extreme example observed so far. Thanks to the fast GROND response we have been able to observe the early rise of a first afterglow component. The complete light curve results

[1] Here we adopt the standard notation $F(\nu,t) \propto \nu^{-\alpha} t^{-\beta}$ for every single portion of the multi-power-law fitting

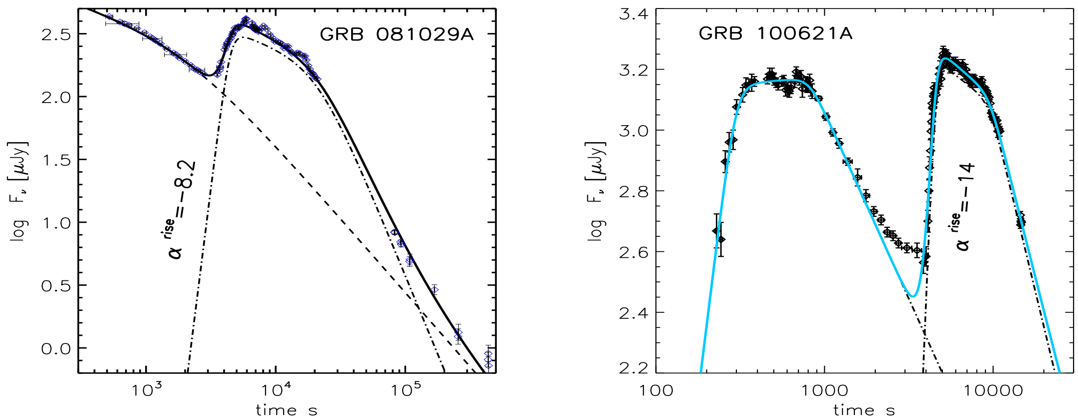

Figure 1: r' band GROND light curve of the afterglow of GRB 081029 (left panel) and J band GROND light curve of the afterglow of GRB 100621A (right panel) modelled as a superposition of two separate components with the value of the second component rise index $\alpha_1^{\rm steep}$ highlighted.

from a sum of 2 smoothly-connected triple power-laws as shown in the right panel of Fig. 1. In this case, the sudden rebrightening is even steeper than the one observed for GRB 081029, with $\alpha^{\rm rise} \approx -14$. The two light curves plotted in Fig. 1 show other similarities other than the prominent optical rebrightening. In both cases the steep rise is followed by a smooth decay phase superposed with several achromatic wiggles and ending with an achromatic break. These features are however not observed in all the bursts in our sample. For example, GRB 100316B shows a very smooth, steeper (with respect to the shallow post-rise decay observed in GRBs 081029 and 100621A) decay after the rebrightening (see Fig. 2). Unfortunately GRB 100621A is at present the only case in which we have a GROND detection of the first afterglow rise.

2.2 Spectral evolution

The great improvement we can report here with respect to the optical rebrightening studies already discussed in the literature is related to the possibility to follow the whole temporal evolution also from the spectral point of view. Since these GRBs are characterised by sharp sudden changes in the light-curve evolution, to extract a Spectral Energy Distribution (SED) from non-simultaneous photometric detections can can result in a wrong estimate of the spectral index β. This is true in particular when the light-curve evolution is strongly chromatic. With GROND we can now for the first time follow the SED by extracting a simultaneous 7-band SED for each single telescope exposure, tracking the light curve with a corresponding β evolution. This is what we show in the plots reported in Fig. 2. All 4 GRBs show a strongly chromatic evolution. The rebrightening is always accompanied by a simultaneous change of the optical-NIR spectral index. In all reported cases, moreover, the new rising component is characterised by a spectrum that is redder than the pre-bump phase. A similar spectral change was observed also in other cases with late optical flattenings like GRB 061126 [4][10] and GRB 071003 [15][3].

In [11], we found that no X-ray rebrightening is observed simultaneously with the optical

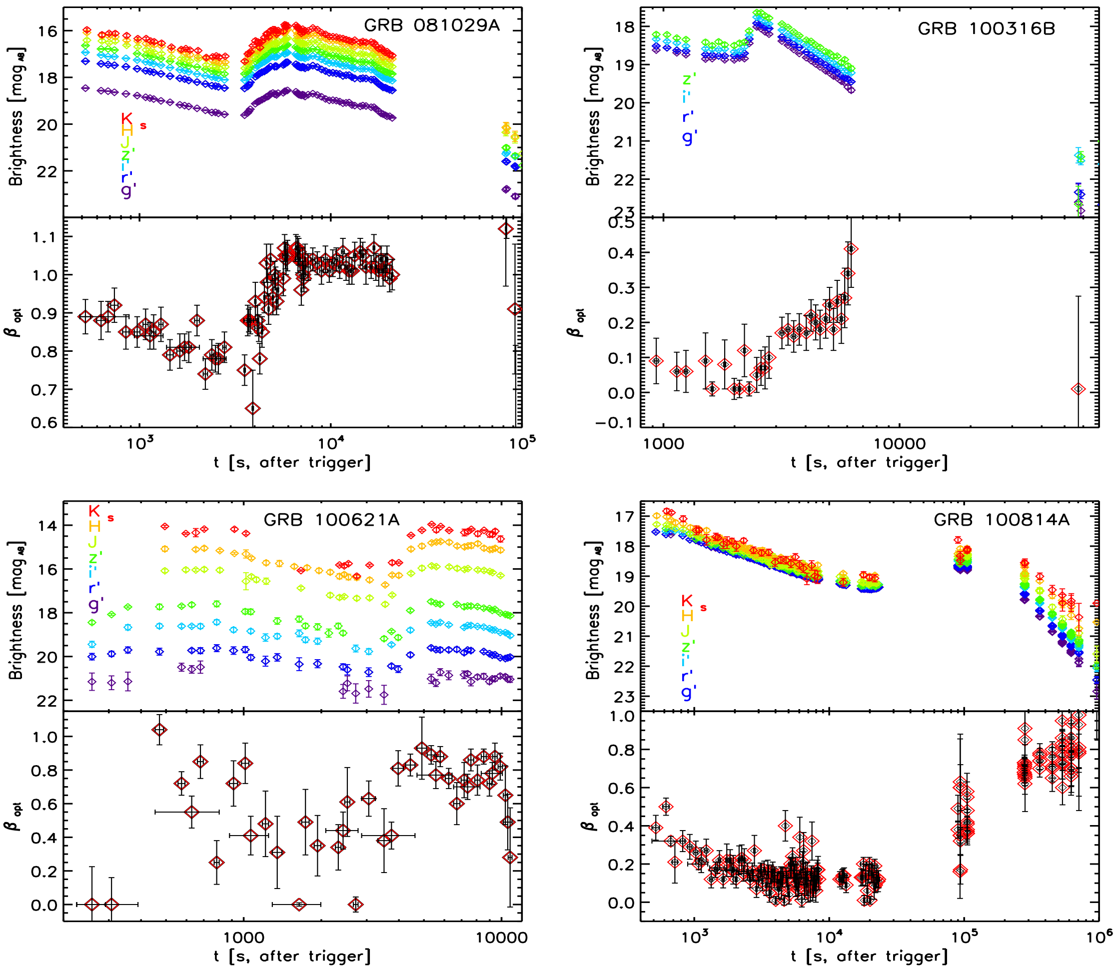

Figure 2: Upper panels: GROND optical-NIR light curves of 4 GRBs showing an optical-NIR rebrightening. Lower panels: evolution of the spectral index β_{opt} obtained from the fitting of the simultaneous observations in the 7 GROND bands. Light curve magnitudes are not corrected for either Galactic and host galaxy dust absorption nor for redshifted Lyman absorption (affecting g' and r' bands in GRB 081029). β_{opt} values are obtained taking into account of the Galactic and possible host galaxy dust absorption.

bump of GRB 081029. When comparing GROND with XRT light curves[2] for the other GRBs in our updated sample, we confirm this finding to be a general feature of these "bumpy afterglows" even if a hint of simultaneous activity (i.e., a small excess of X-ray flux around the optical peak time) can be claimed for both GRB 100814A and GRB 100621A. This last issue will be discussed in a forthcoming paper in preparation.

3. Discussion

The observational features characterising "bumpy afterglows" in our sample are: i) the presence of an extremely fast and bright optical rebrightening some ks after the trigger, ii) a sudden

[2] `http://www.swift.ac.uk/xrt_curves/`

colour evolution during such a rebrightening, and iii) the absence of a simultaneous bump in the X-ray light curve. These features cannot be explained in the framework of the standard external-shock afterglow scenario. This model had been already unsuitable to account for several complex optical afterglow light curves and several modifications have been proposed in the literature. Unfortunately, none of the most commonly used alternative models are able to account for all the 3 common features characterising the events described above. For example, the first model that is usually invoked to explain optical rebrightenings is related to the sudden increase of the external medium density [8] that is expected to occur at the transition boundary of the stellar wind of the progenitor and the surrounding interstellar medium. This effect should be prominent for frequencies $\nu_{\rm m} < \nu < \nu_{\rm c}$[3], and this could explain the absence of an X-ray signature when $\nu_{\rm X} > \nu_{\rm c}$. However, even sharp discontinuities in the density profile or the encounter of the blast wave with a wind-termination shock can only produce smooth and diluted changes in the observed light curve [12]. Other models like the two-component jet [1][2] and the late prompt [3][10] have been proposed in order to explain the complex chromatic evolution of well-sampled long GRBs. In the first, a flattening or a bump in the light curve can be observed if the onset of the afterglow produced by the slower (and wider) jet appears when the afterglow emission of the faster (and narrower) jet is already decreasing fast to due the early-time jet break. According to the late prompt scenario the observed broad-band light curve is composed of the sum of two separate components: the standard forward-shock afterglow emission and a radiation related to a late-time activity of the central-engine sustained by the accretion of fall-back material which failed to reach the escape velocity of the progenitor star. In both models, the nature of the rising component is disentangled from the pre-bump one and this fact allows the sudden colour change observed during the rebrightening. However a steep $\alpha^{\rm rise} < -10$ cannot be produced according to the standard version of these models. Moreover, for the two-component jet, we also find no good agreement with the predicted closure relations.

4. Conclusion

As discussed above, the most commonly invoked scenarios fail to reproduce all the features characterising these fast rebrightenings (see [11] for a more complete discussion on the case of GRB 081029 that can be generalised). This problem can be solved if the starting time of the second component (either in the two-component jet or in the late prompt scenario) is not simultaneous with the GRB trigger but delayed by a few hundred seconds. If this second component is related to a reactivation of the central-engine we can try to identify a signature in other bands. Several examples of a pre-/post-cursor prompt emission activity with delay times of hundreds of seconds are already known and are sometimes accompanied by a late optical rebrightening [5], however, no signature of late gamma emission is observed in the GRBs presented above. Weaker or softer post-cursors could be visible as X-ray flares (like in GRB 071003). In [11] we claimed this possibility but no early XRT coverage was available. Now, we can extend our sample to GRB 100814A and GRB 100621A for which dense early-time coverage in X-rays is available and no flare is observed before the optical bump starts. A clear signature of a late reactivation of the central-engine is therefore

[3]See e.g. [14] for a definition of these characteristic frequencies

not a general feature of this class of events. Recently, [17] proposed a scenario where the collision between shells emitted by the central-engine at delayed times and with different Γ Lorentz factor, can produce sharp optical rebrightenings like the ones we are observing with GROND. In cases like GRB 100621A we can infer the Γ of the first shell from the afterglow onset observation and we can therefore constrain this model with an additional fixed parameter. However a more detailed description of the expected spectral evolution above ν_c is needed for testing the consistency of this model with the observed colour evolution and with the absence of a prominent rebrightening in the X-rays.

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