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SWIFT GRB 060105: DO WE SEE THE EMERGENCE OF A JET COCOON IN A VERY BRIGHT BURST?

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Abstract.
GRB 060105 was detected by *Swift* and Konus-Wind. This event was particularly bright with a bolometric fluence of 7.9×10^{-5} erg cm^{-2} in the 18 keV-2 MeV Konus energy range. GRB 060105 could be a bright high-redshift ($z > 3$) GRB, and possibly one of the most powerful GRBs ever detected with a jet geometry-corrected Gamma-ray energy of $\sim 7.3^{+2.8}_{-2.9} \times 10^{51}$ erg, using a pseudo-redshift of $pz = 4.0 \pm 1.3$ and the Ghirlanda relation. The X-ray light-curve of the burst first exhibits a long shallow decay lasting at least 1100 s showing a spectral hardening, followed by three other temporal segments: (i) a steep temporal decay ($\alpha \sim 3.2$) from ~ 4000 s to $\sim 2.5 \times 10^4$ s after the BAT trigger (T_0), (ii) a shallow decay ($\alpha \sim 0.8$) up to $T_0 + 6.8 \times 10^4$ s, and (iii) a steep decay ($\alpha \sim 2.2$) showing a late spectral softening after $T_0 + 10^5$ s. The initial long shallow decay is unusual for most of the GRBs (except the peculiar event XRF 060218), as well as the late steep decay during the segment (i) of the X-ray light-curve. We argue that the shallow decay is a part of an X-ray flare likely produced by late internal shock or alternatively possibly produced by the shock breakout of a jet cocoon from the envelope of a massive star. The segment (i) of the X-ray light-curve is naturally interpreted as due to curvature effect emission after the shock crossing. The segments (ii) and (iii) can be interpreted as due to the forward shock emission from the jet only in the case of the slow cooling ISM afterglow model. The electron distribution is unusually steep with $p \sim 2.8 - 5.5$ for this burst. We show that during the forward-shock-dominated part of the light-curve, the drop of the cooling frequency through the XRT band with time accounts for the late spectral softening seen in our data.

1 Introduction

The launch of *Swift* (Gehrels et al. 2004) on 20th November 2004 allowed to explore a so-far unexplored temporal region from $\sim 10^2$ s to $\sim 10^4$ s after the prompt emission, i.e. the *early* afterglow of Gamma-ray bursts (GRBs).

Most of the current X-ray light-curves obtained with the XRT (X-Ray Telescope; Burrows et al. 2005) exhibit a *canonical* steep-to-flat-to-steep decay (e.g. Zhang et al. 2006, Nousek et al. 2006, O'Brien et al. 2006). The initial steep decay (I) is commonly interpreted as the tail of the prompt emission produced by curvature effect emission (e.g. Kumar & Panaitescu 2000, Tagliaferri et al. 2005). The flat part (II) of the X-ray light-curve is interpreted as due to energy injection in the blast-wave breaking down its deceleration by the ISM (e.g. Nousek et al. 2006). At later time, the standard afterglow (III) can be seen, when energy injection is no longer sufficient to balance the deceleration of the blast-wave by the ISM (e.g. Mészáros & Rees 1993, Sari et al. 1998). X-ray flares seen in half of the *Swift* bursts during the phases I-II (sometimes in the phase III as well) are often interpreted as due to late internal shocks due to an extended activity of the central source (e.g. Falcone et al. 2006, Godet et al. 2006a, b).

However, a few GRBs show X-ray light-curves different to the *canonical* behaviour: (i) the steep-to-flat decay; (ii) only a steep decay; (iii) an unusual flat-to-steep decay; (iv) the case of the peculiar XRF 060218 associated with the supernova SN 2006aj showing a long X-ray flare, in the 0.3-10 keV XRT band, consisting of a rise of the X-ray light-curve up to ~ 990 s after the BAT trigger, followed by an exponential decay with an e-folding time of ~ 2100 s (e.g. Campana et al. 2006).

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Here, we report the case of the bright burst discovered by the Burst Alert Telescope (BAT; Barthelmy et al. 2005) on 5th January 2006 (Godet et al. 2006c). The observatory automatically slewed and the XRT started to observe 87 s after the BAT trigger (T_0). The refined position on ground is (J2000) RA=$19^{\rm h}50^{\rm m}00.6^{\rm s}$ and Dec= $+46^{\rm d}20'58.3''$ with a total uncertainty radius of 4.5 arc-seconds at a 90% confidence level. This position accounts for the recent improvement of the XRT boresight (Moretti et al. 2006). The burst was also detected around $T_0 - 21$ s by Konus-Wind (Aptekar et al. 1995). The UV/Optical Telescope (UVOT; Roming et al. 2005) detected no optical fading source down to a 3σ limiting magnitude of 20.4 in V-band for an exposure of 29453 s, 20.1 in B-band for an exposure of 5076 s and 20.8 in U-band for an exposure of 23377 s (Schady et al. 2006). Ground telescopes did not find any optical, IR and radio counter-part (e.g. Yonetoku et al. 2006, Frail 2006). Pelangeon & Attéia (2006) reported a pseudo-redshift of $pz = 4.0 \pm 1.3$.

The X-ray light-curve of GRB 060105 is unusual compared to the *canonical* behaviour, since it shows an initial long shallow decay, followed by a steep-to-flat-to-steep decay. The paper is organised as follows: in Section 2, we present the temporal and spectral analysis of the multi-wavelength observations. In Section 3, we investigate the mechanisms producing the spectral and temporal characteristics of the burst. We discuss the possibility that the X-ray data before $\sim T_0 + 2 \times 10^4$ s are produced by the breakout of a jet cocoon.

By convention, we note hereafter the flux in the X-ray band is modelled as $F_\nu \propto \nu^{-\beta} t^{-\alpha}$ where β is the energy spectral index and α is the temporal index. We use the symbol γ to refer to the Lorentz factor. The BAT spectral slope is noted as $\beta_{\rm BAT}$.

2 Data analysis

All the errors cited below are given at a 90% confidence level for one parameter of interest (*i.e.* $\Delta\chi^2 = 2.706$). The X-ray spectra and the X-ray light-curve are corrected to the effect of the pile-up when necessary as well as the effect of the bad columns (for more details, see http://www.swift.ac.uk/xrtdigest.shtml). All the fits were performed within XSPEC v11.3.1 (Arnaud 1996). Hereafter, we take a Galactic absorbing column of $n_H^{\rm Gal} = 1.8 \times 10^{21}$ cm^{-2}, in the direction of GRB 060105, from the 21 cm radio hydrogen measurements (Dickey & Lockman 1990).

2.1 Temporal analysis

The BAT and Konus-Wind light-curves show three main multi-peaked bursts with an overall flat-topped shape (see the panel A1 in Fig. 1). There is softer, weaker emission in the 15-50 keV BAT energy band up to at least 150 s. T_{90} in the 20 keV-2 MeV Konus-Wind energy band is 53.4 ± 0.5 s.

The BAT/XRT light-curve in the 0.3-10 keV energy band is shown in Fig. 1 (panel B1). To extend the BAT light-curve into the 0.3-10 keV energy band, we take the same approach as described in O'Brien et al. (2006), using the mean of the BAT and XRT/WT spectral slopes ($\beta_m \sim 0.5$). To convert in flux the WT and PC count rates, we use the spectral slopes shown in Fig. 1 (the panel B3). A long shallow X-ray decay (Windowed-Timing data) is seen in the beginning of the X-ray light-curve, followed by a steep-to-flat-to-steep decay. Note that the BAT and XRT light-curves do not join smoothly. That suggests that an X-ray flare is present at the junction of the BAT and XRT light-curves.

Assuming that the steep decay seen in the late light-curve (after $T_0 + 4000$ s) is the result of curvature effect emission (e.g. Kumar & Panaitescu 2000) following a long X-ray flare, we fit the X-ray Photon-Counting (PC) data with the following model taking into account the zero time (t_c) effect and the overlapping effects: $F(t) = A\left(\frac{t-t_c}{t_c}\right)^{2+\beta_1} + B_p(t)$, where $\beta_1 = 1.21$ is the spectral index of the first steep decay part from $\sim 1.6 \times 10^4$ s to $\sim 3 \times 10^4$ s. A is a normalisation parameter and $B_p(t)$ is a broken-powerlaw modelling the forward shock component (the flat-to-steep decay seen in the light-curve). The zero time for the B_p component is assumed to be the trigger time T_0 (e.g. Lazzati & Begelman 2006). A good fit is obtained with this model fixing $t_c = 45$ s (i.e. the start time of the X-ray flare). The shallow part of the light-curve after $T_0 + 3.2 \times 10^4$ s has a temporal decay slope of 0.83 ± 0.14, followed by a steeper decay with a slope of $2.21^{+0.28}_{-0.39}$ after $T_0 + 6.8^{+1.9}_{-0.8} \times 10^4$ s.

2.2 Spectral analysis

The time-integrated Konus-Wind spectrum from $T_0 - 21$ s to $T_0 + 37.8$ s is well fit in the 18 keV-13 MeV Konus band by Band function (Band et al. 1993) with a pre-break slope of $0.79^{+0.07}_{-0.05}$, a post-break slope of $2.70^{+0.35}_{-0.73}$, and an energy break of $E_p = 396^{+31}_{-39}$ keV ($\chi^2/\nu = 58/61$). GRB 060105 has a high bolometric (18 keV-13 MeV) fluence of 7.92×10^{-5} erg cm^{-2}. Using the value of the pseudo-redshift ($pz = 4.0 \pm 1.3$), the isotropic energy is $E_\gamma^{iso} \sim 2.6 \times 10^{54}$ erg, and the jet geometry-corrected energy is $7.3^{+2.8}_{-2.9} \times 10^{51}$ erg using the Ghirlanda relation. GRB 060105 could be one of the brightest high-redshift GRBs.

¿From the fits of the WT and PC data, we find excess absorption of $\Delta n_H(z=0) \sim 1.9 \times 10^{21}$ cm^{-2} over the Galactic value [1]. The evolution of the spectral slopes in the X-ray data for different time intervals are shown in the panel B3 in Fig. 1. A clear spectral softening in the PC data is seen after $T_0 + 10^5$ s (see the panels B2 and B3 in Fig. 1).

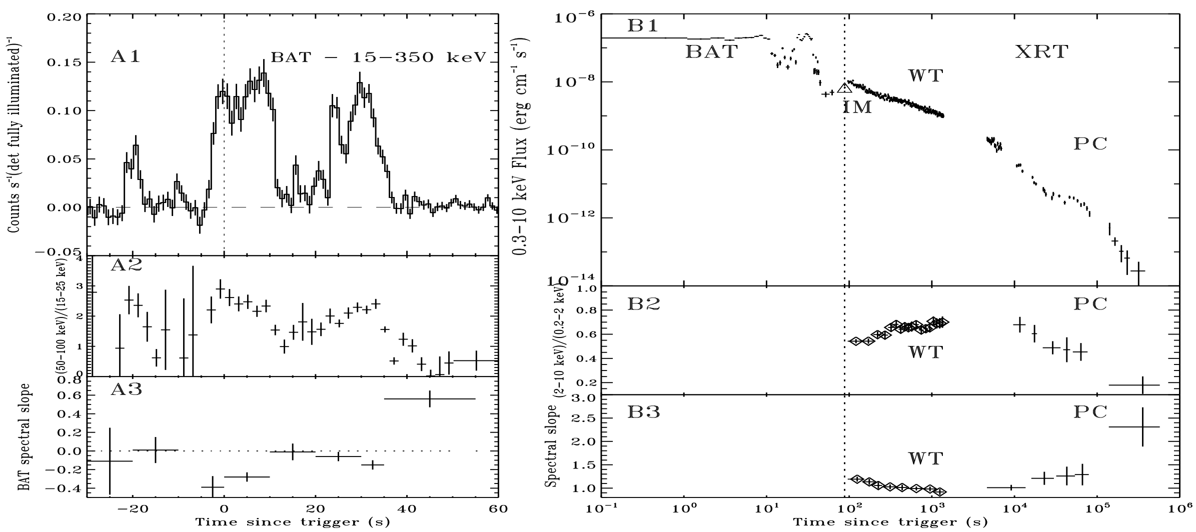

Fig. 1. Temporal and spectral characteristics of the BAT and XRT data. **A1**: Background-subtracted BAT light-curve in the 15-350 keV energy band. The dotted line corresponds to the trigger time; **A2**: the hardness ratio of the 50-100 keV energy band over the 15-25 keV energy band; **A3**: the spectral slope derived using a power-law model to fit the data as a function of time; **B1**: BAT/XRT light-curve in the 0.3-10 keV energy range in units of flux (erg cm^{-2} s^{-1}). The mean of the BAT and XRT/WT spectral slopes ($\beta_m \sim 0.5$) was used to extend the BAT light-curve into the XRT band; **B2**: the hardness ratio of the 2-10 keV energy band over the 0.2-2 keV energy band; **B3**: the spectral slope derived using an absorbed power-law model to fit the data as a function of time (the diamonds for the WT data and the crosses for the PC data). Note that the first two orbits of the PC data being moderately piled-up are not shown in the HR plot.

3 Discussion and conclusion

3.1 The prompt emission

In Section 2.1, we showed that the steep decay seen in the X-ray light-curve after 4000 s can be interpreted as produced by curvature effect. However, none of the other *Swift* bursts clearly shows a curvature component after a shallow decay component. The only known exception is the peculiar burst XRF 060218 which shows a long shallow decay followed by a steep decay (Campana et al. 2006). In this latter burst, the long shallow decay was interpreted by Dai et al. (2006) as produced by a shock crossing process.

According to Dai et al. (2006), the shock was produced when a relativistic outflow interacted with a pre-existing slower shell, leading a forward and reverse shock producing a prompt emission from inverse-Compton scattering of shock breakout thermal photons. The thermal photons could origin from the optically thick hot plasma composing a jet cocoon, when this latter one breaks out and propagates through the stellar envelope

[1] Excess absorption is derived at $z = 0$, because no redshift information is available for this burst.

and/or the extended wind, if any, of a massive star (e.g. Ramirez-Ruiz et al. 2002). We argue here that a similar shock crossing process could be possibly at work to produce the long X-ray flare seen in GRB 060105 (Godet et al. 2006c). Indeed, Pe'er et al. (2006) have shown that the resulting Comptonized spectrum, when the jet cocoon breaks out, could be approximated in some cases by a power-law with a spectral slope of $\beta \sim 1$ in the 0.3-10 keV energy band; which is consistent with the spectral slopes found in the case of GRB 060105. Moreover, the steep decay from $\sim 4000\,$s to $\sim 2 \times 10^4\,$s seen in the X-ray light-curve of GRB 060105 can be naturally interpreted as due to a combination of curvature effect emission after the shock crossing, and the spread of the arrival times of the X-ray photons due to the multiple Compton scattering inside the cocoon.

Alternatively, the X-ray flare could be produced by a long internal shock. Then, the shell width producing the X-ray flare ($R_{shell} \sim v_s \Delta t$, where Δt is the shock crossing time and $v_s \sim c$ is the res-frame speed of the shock) would be approximately two orders of magnitude larger than that producing the total Gamma-ray prompt emission ($R_{burst} \sim cT_{90}/(1+z)$). According to the internal shock model, shells of matter thicker than those producing the prompt emission could be produced at later time due to longer accretion episodes around the central new-born compact object (e.g. Proga & Zhang 2006, Perna et al. 2005).

3.2 The forward shock emission

The X-ray data after $\sim T_0 + 2.5 \times 10^4\,$s suggest that the fireball expands in constant density ISM (e.g. Sari et al. 1998) with $\nu_m < \nu_X < \nu_c$ (corresponding to a slow cooling of the electrons), where ν_c and ν_m are the cooling and synchrotron frequencies, respectively. The situation where $\nu_X < \nu_c$ could be encountered for relatively low values of magnetic field energy and density, and/or high values of the parameter Y, i.e. the energy ratio between the inverse Compton component and the synchrotron component (e.g. Zhang et al. 2006). From the closure relations in that regime, we find an unusual steep value of the power of the electron distribution with $2.9 < p < 4.4$. The late spectral softening after $\sim T_0 + 10^5\,$s is then due to the crossing of the cooling frequency through the XRT band ($\nu_X > \nu_c$). From the closure relations in that regime, we compute $p = 4.6^{+0.9}_{-0.8}$, which is consistent with the above p-values, and a temporal decay slope of $\alpha = 2.9 \pm 0.2$. Note that this decay index is close to that found in Section 2.1 ($\alpha = 2.21^{+0.28}_{-0.39}$).

Most of the GRBs present p-values close to the commonly used value of 2-2.4, while a small fraction seems to present hard electron distributions with $p < 2$ (e.g. Zhang et al. 2006). The GRBs showing steep electron distributions ($p > 3$) are relatively rare. However, O'Brien et al. (2006) suggested that a few *Swift* bursts could have large p-values ($p > 3$; see also Groot et al. 1998).

Using $pz \sim 4.0$, we derived a jet break time of $\sim T_0 + 3.1$ days; which is consistent with our light-curve.

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