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GRB 050904 AS SEEN BY SWIFT AND TAROT

B. Gendre[1], A. Galli[1], A. Corsi[1], A. Klotz[2], L. Piro[1], G. Stratta[3], M. Boër[4], Y. Damerdji[4] and J.L. Atteia[3]

Abstract. We present optical and X-ray observations of GRB 050904 obtained with TAROT and Swift. We performed temporal and spectral analysis of the XRT data and found evidence for a variable absorption. The early X-ray flare and the following afterglow spectral properties are similar. In the optical band, we observe a flare simultaneous with the X-ray one. In the framework of the external shock scenario, we consider different models to explain the simultaneity of the X-ray and optical flares and the late afterglow emission. Considering both the spectral and temporal information we compare the model predictions with the observed data. The overall behaviour of the early afterglow is compatible with a fireball expanding in a wind environment. Finally, the late optical flattening might be explained by the effect of a termination shock.

1 Introduction

Long Gamma-Ray Bursts (GRBs) are cosmological explosions thought to be produced by a massive star (for a review see Piran 2005). The SWIFT satellite, has shown that strong flaring activity in the early X-ray afterglow originally found in a few cases by BeppoSAX is a common phenomenon (O'Brien et al. 2006). The origin of these X-ray flares is not clear, and several models have been proposed. Another interesting aspect of the afterglow studies is the constraints one can put on the absorption around the burst (Stratta et al. 2004). This is a key issue for high-z bursts, as it allows to study the metal enrichment of the Universe at early epochs. A final aspect of the afterglow evolution is the problem of the surrounding medium of the burst. Since long GRBs are related with massive stars, one should expect a wind environment around them, possibly stopped by a dense surrounding interstellar medium (Chevalier et al. 2004). The interface between these two media is called the termination shock. Here we present a multi-wavelength analysis of the GRB 050904 afterglow and show its consistency with the occurence of a termination shock.

GRB 050904 was triggered by the BAT instrument on board the SWIFT satellite on September 4th, 2005. The narrow field instruments XRT observed the field of GRB 050904 about 160 seconds after the trigger and detected an X-ray transient (Cummings et al. 2005). The first optical detection was made by TAROT (Boër et al. 1999), which observed a faint optical afterglow in a clear filter (Boër et al. 2006). Larger optical and infrared telescopes imaged the field of view 3 hours after the burst and detected an infrared counterpart (Haislip et al. 2005). The spectroscopic redshift measured by the Subaru telescope is z = 6.29 (Kawai et al. 2005). This burst is currently the more distant burst ever observed, and also presented strong and long lasting multi-wavelength flaring activities (Kawai et al. 2005; Watson et al. 2006; Boër et al. 2006).

2 Data reduction and analysis

The X-ray and optical data reduction is explained in Gendre et al. (2006). All errors for the fit parameters quoted in the paper are given at the 90 % confidence level for one interesting parameter.

[1] IASF-Roma/INAF, via fosso del cavaliere 100, 00133 Roma, Italy
[2] CESR, 9 avenue du Colonel Roche, 31400 Toulouse, France
[3] LATT, Observatoire Midi-Pyrénées, 14 avenue Edouard Belin, 31400 Toulouse, France
[4] Observatoire de Haute-Provence, 04870 St Michel l'Observatoire, France

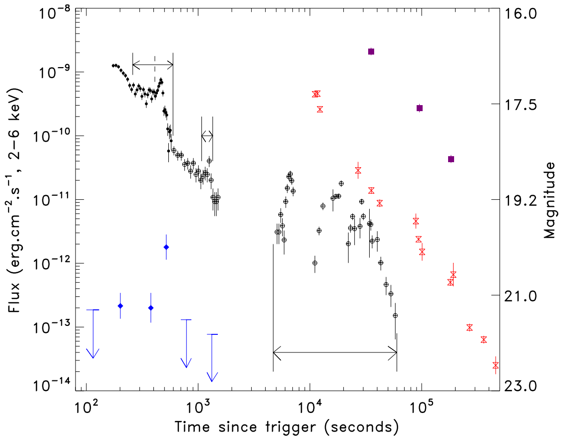

Fig. 1. Multi-wavelength light curve of GRB 050904. We present the X-ray data (black points) taken in the 2.0-6.0 keV band with filled circles (WT mode data) and open circles (PC mode data), the TAROT I_T band data with blue diamonds, the H data with purple squares and the J data with red symbols (from Haislip et al. 2005; Tagliaferri et al. 2005). For clarity, offsets by +6 and -1.5 magnitudes have been applied to TAROT data and H band data respectively. We indicate the intervals excluded for the temporal fit of the X-ray data (solid horizontal arrows). The vertical dashed line indicate the position of the transition between the plateau and the first flare.

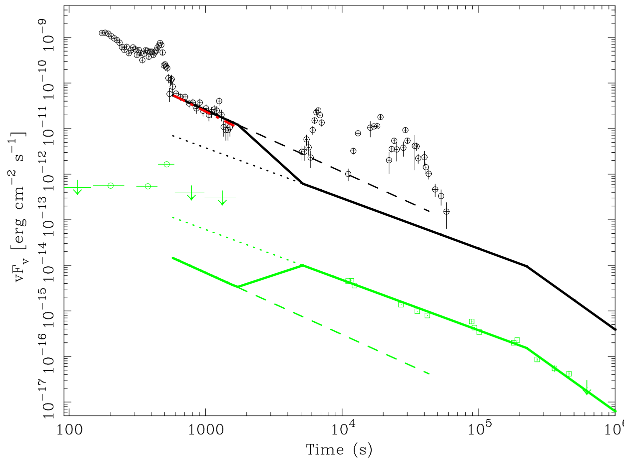

Fig. 2. Global modelling of the broad-band data using a wind plus ISM scenario (solid lines). We present in black the X-ray data and in green the optical data (rescaled by a factor 0.01 for clarity purpose). The red-dot-dashed line is the best fit decay law to the X-ray data between $\sim$ 600 s and $\sim$ 1700 s. The dotted lines represent the extrapolation of the ISM model by Frail et al. (2006) to early times. The dashed lines are the extrapolation of the wind model to late times. We assumed an instantaneous wind-to-ISM transition at $t \sim 1700$ s, smoothed by the effect of the fireball curvature.

We present in Fig. 1 the multi-wavelength light curve of this burst. TAROT has observed a flare in the I_T band which is coincident with one X-ray flare (Boër et al. 2006). The X-ray light curve shows a very complicated evolution, with several flares. We fitted the early X-ray light curve ($t < 2000$ s) excluding all data points between the start and the end of all flares and also the data located in the plateau (see Fig. 1). We have fit separately the data before and after the flare using a power law. The early decay is 2.5 ± 0.2 ($\chi^2_\nu = 1.05$, 13 d.o.f.) and the late decay 1.5 ± 0.2 ($\chi^2_\nu = 0.72$, 14 d.o.f.). The spectra were fitted with a simple power law, absorbed by our galaxy (N_H value fixed to the galactic one) and by local absorbers at redshift 6.3. We detect an excess of absorption only during the first 264 s of the observation. The hypothesis of a constant N_H is rejected at the 99.5 % confidence level using a χ^2 test (χ^2=13.41/3 d.o.f.).

3 The X-ray observations before the first flare

The hard γ-ray emission is observed up to the start of the first X-ray flare (Sakamoto et al. 2005); the X-ray emission before the first flare has temporal and spectral indexes compatible with the tail of the prompt one (closure relationship $\delta = 2 + \alpha$, Kumar & Panaitescu 2000); and the X-ray spectral index observed before the start of the flare is comparable to the γ-ray one: this part of the observations may be linked to the prompt emission. The decrease of the measured equivalent column density that we observe may be the evidence of a progressive photo-ionization of the initially cold gas in which the GRB occurs by the burst itself (Perna & Loeb 1998).

4 The surrounding medium : observation of a termination shock

We have investigated on the surrounding medium of GRB 050904, using the X-ray data between the end of the first flare (t$\sim$580 s) and $\sim$ 1666 s, and the optical data taken between 0.5 and 2.6 days. We list our results in Table 1. An ISM scenario is only in marginal agreement with the early X-ray data. On the other hand,

Table 1. Closure relationships in the standard fireball model computed using the spectral and temporal information. We give the relationships for the J band after 0.5 days.

Medium class	Cooling regime	Specific frequency position	Closure relationship	Expected value	X-ray (0.5-10.0 keV) (582-1666 s)	optical (J band) (0.5-2.6 days)
Isotropic Wind	Fast	$\nu_m < \nu$	$\delta - 1.5\alpha$	-0.5	0.6 ± 0.3	-1.1 ± 0.6
		$\nu_m > \nu$	$\delta - 0.5\alpha$	0.0	1.2 ± 0.3	0.1 ± 0.4
	Slow	$\nu_c < \nu$	$\delta - 1.5\alpha$	-0.5	0.6 ± 0.3	-1.1 ± 0.6
		$\nu_c > \nu$	$\delta - 1.5\alpha$	0.5	0.6 ± 0.3	-1.1 ± 0.6
Isotropic ISM	Fast	$\nu_m < \nu$	$\delta - 1.5\alpha$	-0.5	0.6 ± 0.3	-1.1 ± 0.6
		$\nu_m > \nu$	$\delta - 0.5\alpha$	0.0	1.2 ± 0.3	0.1 ± 0.4
	Slow	$\nu_c < \nu$	$\delta - 1.5\alpha$	-0.5	0.6 ± 0.3	-1.1 ± 0.6
		$\nu_c > \nu$	$\delta - 1.5\alpha$	0.0	0.6 ± 0.3	-1.1 ± 0.6

the late broad-band (radio-to-X-rays) observations clearly agree with an ISM environment having a very high density (Frail et al. 2006), but as one can see in Fig. 2, the extrapolation of this model at early times, cannot describe the data. We thus conclude that while an ISM describes well the late broad-band observations (Frail et al. 2006), it does not reproduce satisfactorily the early X-ray data.

A wind environment is clearly favored by the early X-ray observations ($\nu_c > \nu_X$). This model cannot fit the late optical data because in a wind environment ν_c increases with time (Chevalier & Li 2000). Combined with the results by Frail et al. (2006), this suggests that the fireball could be expanding into a medium whose density profile at small distances is that expected for a wind ($n \propto r^{-2}$), and becomes constant at larger radii. In this hypothesis, a wind termination shock should mark the transition. We estimate its crossing time (from the observations) to be located between 0.019 days and 0.5 days, and derive its position, R_t, to be 0.018 pc $< R_t <$ 0.041 pc.

5 Multi-wavelength analysis of the first flare

5.1 Delayed external shock scenario

The spectra of the first flare is softer than the preceding one and is consistent with the afterglow emission. Similar properties have been previously observed in other bursts, and have been explained in the framework of a delayed external shock (Sari & Piran 1999; Piro et al. 2005; Galli & Piro 2006). In this framework both the X-ray and the optical flares are produced by the external shock, thus explaining the coincidence between the two flares. We used the model of Galli & Piro (2006), that take this delay into account, to check if it can explain the multi-wavelength flare. However, no solution can reproduce the optical flare in a wind case : the calculated optical flux at the time of the flare is about 1.5 order of magnitude below the measured flux. In fact, with the cooling frequency ν_c above the X-ray band, the predicted optical to X-ray spectral index is $\alpha_{ox} \sim 0.6$, while we observe $\alpha_{ox} \sim 1.1$.

5.2 Other possible two-component scenarios

The impossibility of extrapolating the X-ray flux in the optical band rules out all single component scenarios, where the optical flux should be the power law extention of the X-ray one.

In the standard fireball model, when a relativistic ejecta moves into the cold ISM, two shocks form, an outgoing one that propagates into the ISM (the Forward Shock, FS) and a Reverse Shock (RS) that propagates into the ejecta (Sari & Piran 1999). Kobayashi et al. (2005) suggested the possibility of explaining X-ray flares via synchrotron self-Inverse Compton (IC) radiation from the RS. The prompt optical flare should be associated with synchrotron emission from the RS while the simultaneous X-ray flare to up-scattering via the IC process in the X-rays. In a thin shell fireball expanding in an ISM, both the low and high energy emissions should thus peak at the decelation time (Sari 1997) and the temporal coincidence between the optical and the X-ray flares would be a natural expectation for this model. Using an additional emission mechanism like IC gives a natural explanation for the impossibility of extrapolating the spectrum of the X-ray flare down to the optical data points. To explain the broad-band spectrum, the RS IC peak flux should be a factor of $\sim 1.4 - 4$ greater than the RS synchrotron flux at the same frequency. As shown by Kobayashi et al. (2005), a factor as large as 6 can be explained with a reasonable choice of parameters. However, one should also expect a shallow decay of the flare (Kobayashi et al. 2005), $\delta \sim 2.4$ rather than the observed $\delta \sim 12.6$.

Wei et al. (2006) have shown how the steep temporal decay of the X-ray flare can be produced invoking a late internal shock model, where the optical flash comes from late internal shock synchrotron emission while the first X-ray flare is produced by late internal shock IC emission. In this model the temporal coincidence between the optical and the X-ray flare is a natural expectation and there is no optical to X-ray extrapolation problem.

Finally, Zou et al. (2005) interpreted the early-to-late time multi-band observations assuming that all the highly variable X-ray emission of GRB 050904 originated from internal shocks. However, we notice that the optical flare and the overall decay behavior of the X-ray light curve still need to be modeled in detail. We also underline that this model assumes a super-long central engine activity, i.e. that the shell ejection process lasts $10^4 - 10^5$ s.

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