Optical emission from GRB 050709: a short/hard GRB in a star-forming galaxy[⋆]

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ABSTRACT

We present optical observations of the short/hard gamma-ray burst GRB 050709, the first such event with an identified optical counterpart. The object is coincident with a weak X-ray source and is located inside a galaxy at redshift $z = 0.1606 \pm 0.0002$. Multiband photometry allowed us to study the broad-band spectral energy distribution. Late-time monitoring places strong limits on any supernova simultaneous with the GRB. The host galaxy is not of early type. Spectra show that the dominant stellar population is relatively young (~1 Gyr), and that ongoing star formation is present at a level of 2–3 L/L_* $M_\odot$ yr^{-1}. This is at least 2 orders of magnitude larger than that observed in the elliptical hosts of the short GRB 050509B and GRB 050724. This shows that at least some short GRBs originate in a young population. Short/hard GRB models based on the merger of a binary degenerate system are compatible with the host galaxy characteristics, although there is still the possibility of a connection between young stars and at least a fraction of such events.

Key words. radiation mechanisms: non-thermal – gamma rays: bursts – gamma rays: individual GRB 050709

1. Introduction

Gamma-ray bursts (GRBs) are short pulses of gamma rays occurring at random positions in the sky. Two classes of GRBs are currently known, characterised by different durations and spectral properties (Kouveliotou et al. 1993). Long GRBs (typically lasting 10–100 s) are on the average softer than the short ones (duration < 2 s). Over the past years, great advances have been made in understanding the former class, thanks to the observation of their optical and radio counterparts. However, until recently, no optical emission from short GRBs had been identified (Hurley et al. 2002), leaving fundamental questions about their nature, progenitors and distances unanswered.

Recently, thanks to the *Swift* and HETE-2 satellites, accurate and rapid localisations of short GRBs have become available, enabling deep, sensitive searches at long wavelengths.

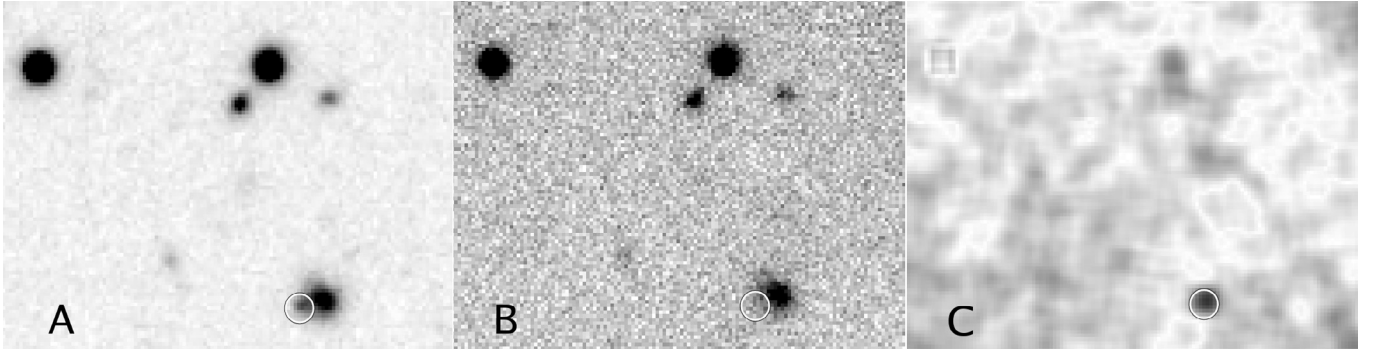[⋆] Based on observations carried out at ESO telescopes under programmes Id 075.D-0787 and 075.D-0468.

Fig. 1. *R*-band image of the field of GRB 050709, on 2005 Jul. 12.41 (A) and 20.42 (B). Panel C shows the result of the subtraction, evidencing a fading source coincident with the *Chandra* counterpart (circle). The boxes cover a region $30'' \times 20''$ wide.

Swift discovered a weak X-ray counterpart to GRB 050509B (Gehrels et al. 2005), located $\sim 11''$ away from a bright elliptical galaxy at $z = 0.2248$ (Bloom et al. 2005; Hjorth et al. 2005a; Castro-Tirado et al. 2005). An early-type galaxy (Gorosabel et al. 2005) is also associated with GRB 050724 (Barthelmy et al. 2005) at $z = 0.257$ (Prochaska et al. 2005), the only other event for which an optical afterglow was singled out inside the host (Berger et al. 2005a; D'Avanzo et al. 2005). Finally, the line of sight of GRB 050813 (Retter et al. 2005) lies towards a galaxy cluster at $z = 0.722$. A few elliptical galaxies were identified inside the XRT error circle, again supporting the association with early-type galaxies (Gladders et al. 2005; Berger 2005b; Prochaska et al. 2005).

GRB 050709 was discovered by HETE-2 on 2005 Jul. 9.94209 UT (Villasenor et al. 2005). Its prompt emission consisted of a single pulse lasting 70 ms in the 3−400 keV energy band, followed by a weaker, soft bump ~ 100 s long. This second episode may be due to the afterglow onset (Villasenor et al. 2005), or to flaring activity (Barthelmy et al. 2005; King et al. 2005; Perna et al. 2005). In any case, the prompt emission properties are consistent with those of a short/hard GRB.

Follow-up observations with the *Chandra* X-ray observatory revealed a faint, uncatalogued X-ray source inside the HETE-2 error circle (Fox et al. 2005a). At the coordinates $\alpha_{J2000} = 23^h01^m26\overset{s}{.}9$, $\delta_{J2000} = -38°58'39\overset{''}{.}5$ ($0\overset{''}{.}4$ error), it was coincident with a pointlike object embedded in a bright galaxy (Jensen et al. 2005) at $z = 0.16$ (Price et al. 2005a). The variability of this source led Price et al. (2005b) to propose it as the optical counterpart of GRB 050709.

2. Observations and data analysis

We observed the field of GRB 050709 with the ESO Very Large Telescope (VLT), using the FORS 1 and FORS 2 instruments. In our first images, taken on 2005 Jul. 12, the pointlike object reported by Jensen et al. (2005) was clearly visible in the *V* and *R* bands (Fig. 1). Its coordinates are $\alpha_{J2000} = 23^h01^m26\overset{s}{.}96$, $\delta_{J2000} = -38°58'39\overset{''}{.}3$ ($0\overset{''}{.}25$ error), fully consistent with the *Chandra* position. The object lies inside a bright galaxy ($\approx 1\overset{''}{.}2$ away from its nucleus), whose magnitudes are $V = 21.35 \pm 0.07$, $R = 21.08 \pm 0.07$, and $I = 20.63 \pm 0.08$. To search for brightness variations, we monitored the field at several epochs. Data analysis was performed by adopting a

Table 1. Observation log and photometry of the transient source. Errors are at the 1σ confidence level, while upper limits are at 3σ. Data were not corrected for Galactic extinction.

Date (UT)	Instrument	Exp. (min)	Filter	Magnitude
2005/07/12 09:44	FORS 2	6	*V*	24.38 ± 0.10
2005/07/14 07:21	FORS 1	6	*V*	>25.00
2005/07/20 10:16	FORS 1	6	*V*	(reference)
2005/07/30 02:37	FORS 2	9	*V*	>25.20
2005/07/12 09:57	FORS 2	5	*R*	23.83 ± 0.07
2005/07/20 10:07	FORS 1	6	*R*	(reference)
2005/07/30 02:54	FORS 2	50	*R*	>25.00
2005/07/12 09:32	FORS 2	10	*I*	>23.25
2005/07/14 07:32	FORS 1	5	*I*	>24.10
2005/07/18 06:38	FORS 1	20	*I*	(reference)
2005/07/30 04:10	FORS 2	9	*I*	>23.50

subtraction technique (Alard & Lupton 1998), well suited to identify variable objects even when blended with nearby sources. The pointlike object was found to be variable (at the $\sim 10\sigma$ level), being undetectable from Jul. 14 onwards. This confirms the independent finding of Hjorth et al. (2005b). Magnitudes of the variable source were computed assuming a negligible flux in the reference epoch (see Table 1). Photometry of the transient was performed by inserting artificial stars of known brightness and calibrated by observing Landolt standard fields.

On Jul. 30 we took medium-resolution spectra of the host galaxy. Observations were carried out with the FORS 2 instrument at the VLT-UT1, with the 300V grism, covering the wavelength range 6000−9200 Å (6 Å *FWHM*). From the detection of several emission lines, among them Hα, Hβ, and [O II], we derived a redshift $z = 0.1606 \pm 0.0002$. This is consistent with the results of Fox et al. (2005b). Therefore, the rest-frame *B*-band luminosity of the host is[1] $L_B \sim 3.5 \times 10^{42}$ erg s^{-1} ($\sim 0.10 L_*$, assuming $M_B^* = -20.13$ as determined from the SDSS survey; Blanton et al. 2003) and the candidate afterglow lies at a projected distance of ≈ 3.3 kpc from the galaxy core.

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[1] Assuming a cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $h_0 = 0.71$.
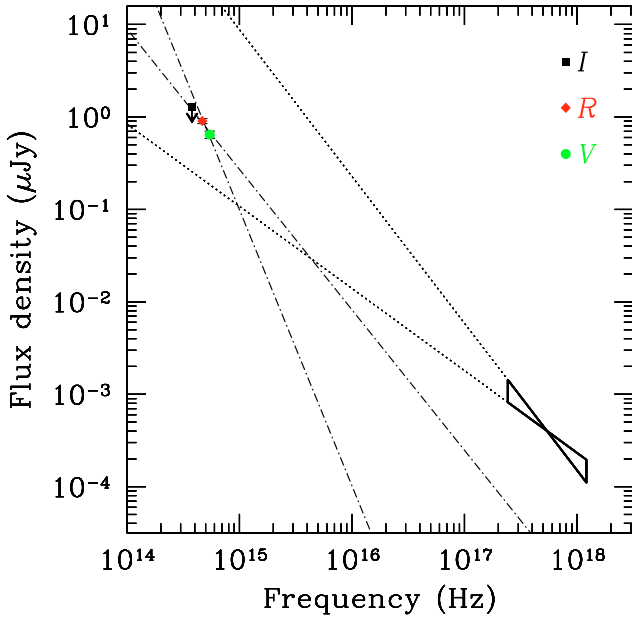
Fig. 2. Broad-band spectral energy distribution of the afterglow of GRB 050709 on Jul. 12.4 UT. The bow-tie shaped region represent the simultaneous X-ray spectrum taken from *Chandra* (Fox et al. 2005b). The dot-dashed and dotted lines indicate the extrapolation of the optical and X-ray spectra, respectively.

Fig. 3. Details of the GRB 050709 host galaxy spectrum close to the Hα and Hβ lines, showing that the narrow emission emissions are superimposed on wider absorption features.

3. Discussion

Assuming a power-law flux decay ($F(t) \propto t^{-\alpha}$), our observations constrain α to be greater than 1.0 in the V band (3σ upper limit). This limit is consistent with the optical decay found by Fox et al. (2005b) using HST data between 5 and 10 d after the GRB (see also Hjorth et al. 2005b). A similar limit was also put to the X-ray afterglow decay. Flaring activity was reported in X-ray light curve (Fox et al. 2005b). Given the limited available data, it is difficult to say whether a similar behaviour was present also in the optical band. Our measurements on Jul. 12 are nearly simultaneous with the first *Chandra* observation, so we can construct the broad-band spectral energy distribution (Fig. 2). The X-ray spectral index is typical for long GRB afterglows (De Pasquale et al. 2003; Nousek et al. 2005). The extrapolation of the X-ray spectrum matches the optical flux (that is, the optical-to-X-ray slope $\beta_{\rm OX} = 1.1$ is consistent with the X-ray slope $\beta_{\rm X} = 1.24 \pm 0.35$). The spectrum corresponding to the optical colours is quite red ($\beta_{\rm opt} = 2.3 \pm 0.7$), but given its large uncertainty it is consistent with $\beta_{\rm OX}$ at the 1.7σ level. Small dust extinction ($A_{\rm V} \approx 0.2$ mag; Fox et al. 2005b) would make the intrinsic color bluer and fully consistent with the X-ray slope, so that the optical and X-ray emission may constitute a single component. However, the sparseness of the data prevents us from drawing any robust conclusion.

The properties of the host galaxy are intriguing. Its colours are consistent with those of an irregular galaxy at $z \approx 0.2$ (Fukugita et al. 1995), and are much bluer than those of ellipticals (like those associated with other short GRBs). Moreover, hints of morphological structure are seen in our best-seeing images. A close inspection of the spectrum shows that both the Hα and Hβ lines have a narrow emission component

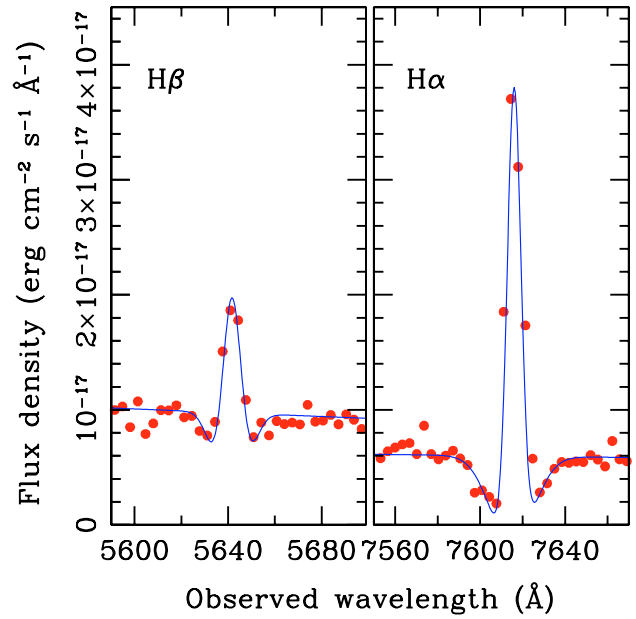($FWHM < 6$ Å) partially filling a wider ($\sim$12 Å $FWHM$) absorption feature (Fig. 3). This classical signature (Dressler & Gunn 1983) identifies a dominant stellar population $\sim$1 Gyr old (mostly A-dwarf stars), together with a younger, hotter component. As indicated from the prominent nebular emission lines, star formation is still present. From the Hα and [O II] emission lines (luminosities 2.62×10^{40} and 2.45×10^{40} erg s^{-1}, respectively), we infer a star formation rate of 0.21 and 0.34 $M_\odot$ yr^{-1} (Kennicutt 1998), which corresponds to $\sim$2–3.5 $M_\odot$ yr^{-1} once normalised to L_*. This is significantly less than that typically observed in long GRB host galaxies (Christensen et al. 2004), but much larger than that in the hosts of GRB 050509B[2] (Bloom et al. 2005) and GRB 050724 (Berger et al. 2005a), by factors of >50 and >150, respectively.

The most popular model for short-hard GRBs is the merger of a binary compact object system (e.g. Eichler et al. 1989). Such events can occur in an late-type, star-forming galaxy (Belczyński & Kalogera 2001), and give rise to short GRBs (Perna & Belczyński 2002). Since the merging timescales may be of the order of 10 Myr, small offsets between the explosion site and the galaxy core are possible. Therefore, GRB 050709 might have been produced in a tightly bound system, with a short merging time, similar to GRB 050724 (Berger et al. 2005a). However, we also note that according to the standard Faber-Jackson relation, the escape velocity from the GRB 050709 host is quite large (about 300 km s^{-1}), so that only a fraction of binary systems may be able to escape its potential well. In this case, a larger delay ($\sim$1 Gyr) would be consistent both with the observed offset and with the age of the older stellar population. A large instantaneous star formation

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[2] Note, however, that many blue galaxies were identified inside the XRT error circle.
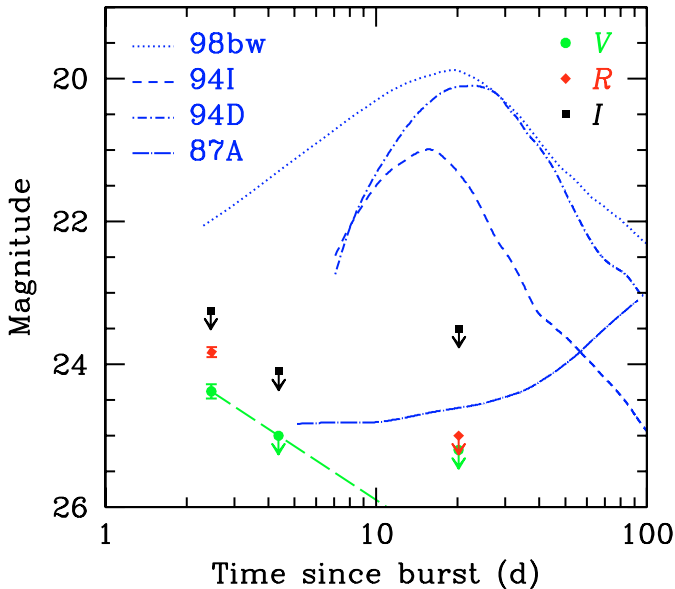
Fig. 4. Light curve of the GRB 050709 afterglow (points), compared to those of several SNe (*R* band). Zero extinction is assumed at the GRB site.

rate would not be expected in this case, even if this does not pose any problem for the merger model.

The presence of pronounced star formation activity in the host galaxy of GRB 050709, however, prompts us to investigate whether this event could be directly related to young stars. Recently, it was proposed that short GRBs may be produced by giant flares from soft gamma-ray repeaters (e.g. Hurley et al. 2005). However, the luminosity of GRB 050709 would be a factor $\sim 10^3$ larger than that of the giant flare from SGR 1806-20. The prompt emission properties also make this hypothesis unlikely (Villasenor et al. 2005). Furthermore, our photometry can put strong constraints on the presence of an unextinguished supernova (SN) exploded simultaneously with the GRB (see Fig. 4). Our limits impose a SN $\gtrsim$ 100 times fainter than a typical type-Ia SN or a bright hypernova like SN 1998bw. Also fainter events like SN 1994I and even SN 1987A are incompatible with our data. An association with a SN seems therefore ruled out for GRB 050709 (see also Hjorth et al. 2005a,b; Fox et al. 2005b). The properties of the GRB 050709 host are however consistent with the model proposed by MacFadyen et al. (2005), which advocates a collapsing neutron star accreting from a close non-compact companion. Such model would also naturally explain the flares observed in the X-ray light curve.

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