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Multicolor observations of the afterglow of the short/hard GRB 050724*

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ABSTRACT

Context. New information on short/hard gamma-ray bursts (GRBs) is being gathered thanks to the discovery of their optical and X-ray afterglows. However, some key aspects are still poorly understood, including the collimation level of the outflow, the duration of the central engine activity, and the properties of the progenitor systems.
Aims. We want to constrain the physical properties of the short GRB 050724 and of its host galaxy, and make some inferences on the global short GRB population.
Methods. We present optical observations of the afterglow of GRB 050724 and of its host galaxy, significantly expanding the existing dataset for this event. We compare our results with models, complementing them with available measurements from the literature. We study the afterglow light curve and spectrum including X-ray data. We also present observations of the host galaxy.
Results. The observed optical emission was likely related to the large flare observed in the X-ray light curve. The apparent steep decay was therefore not due to the jet effect. Available data are indeed consistent with low collimation, in turn implying a large energy release, comparable to that of long GRBs. The flare properties also constrain the internal shock mechanism, requiring a large Lorentz factor contrast between the colliding shells. This implies that the central engine was active at late times, rather than ejecting all shells simultaneously. The host galaxy has red colors and no ongoing star formation, consistent with previous findings on this GRB. However, it is not a pure elliptical, and has some faint spiral structure.
Conclusions. GRB 050724 provides the most compelling case for association between a short burst and a galaxy with old stellar population. It thus plays a pivotal role in constraining progenitors models, which should allow for long delays between birth and explosion.

Key words. gamma rays: bursts – galaxies: fundamental parameters

1. Introduction

Our knowledge of the short/hard class of gamma-ray bursts (GRBs; Dezalay et al. 1991; Kouveliotou et al. 1993) has substantially improved since the launch of the *Swift* and HETE-2 satellites (Gehrels et al. 2004; Ricker et al. 2002). At the time of writing (2007 April), some 25 events had been accurately localized, and, for a significant fraction of them, X-ray (~65%), optical (~30%) and radio (~8%) afterglows were detected (Gehrels et al. 2005; Villasenor et al. 2005; Fox et al. 2005; Hjorth et al. 2005a; Covino et al. 2006; Barthelmy et al. 2005; Berger et al. 2005; Soderberg et al. 2006; Burrows et al. 2006; La Parola et al. 2006; Levan et al. 2006; de Ugarte Postigo et al. 2006; Roming et al. 2006; Berger et al. 2007). This has made possible the identification of their host galaxies (for most of those with arcsecond localization: Bloom et al. 2006; Hjorth et al. 2005b; Castro-Tirado et al. 2005; Prochaska et al. 2006; Gorosabel et al. 2006; Ferrero et al. 2006; Berger et al. 2007). We refer to Nakar (2007) for a recent review on the observational status and its implications. Despite this progress, the study

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Table 1. Log of the observations of GRB 050724. All measurements were carried out using the FORS 1 instrument of the ESO VLT UT2 (Kueyen). Upper limits are at the 3σ confidence level. The epochs marked as "Reference" were used as late-time templates for the subtraction process, and the afterglow brightness cannot be computed from these images. The magnitudes are not corrected for Galactic or intrinsic extinction.

Mean time t (UT)	$t - t_0$ (day)	Filter/ grism	Exposure time (s)	Seeing (″)	Airmass	Magnitude
2005 Jul. 25.01581	0.49210	I	3×180	1.0	1.01	21.18 ± 0.03
2005 Jul. 25.97533	1.45162	I	3×180	0.8	1.06	23.22 ± 0.12
2005 Jul. 27.98413	3.46042	I	3×180	0.8	1.04	25.53 ± 0.33
2005 Jul. 30.11632	5.59261	I	4×180	0.5	1.14	Reference
2005 Jul. 25.00747	0.48376	R	3×180	1.1	1.02	21.85 ± 0.04
2005 Jul. 25.98390	1.46019	R	3×180	1.0	1.05	23.66 ± 0.09
2005 Jul. 26.96903	2.44532	R	1×60	0.8	1.07	>24.4
2005 Jul. 27.97569	3.45198	R	3×180	0.8	1.05	>24.8
2005 Jul. 30.10470	5.58099	R	4×180	0.5	1.11	Reference
2005 Aug. 25.98876	32.46505	R	8×120	0.7	1.01	>25.7
2005 Jul. 24.99906	0.47535	V	4×120	0.9	1.03	22.49 ± 0.03
2005 Jul. 27.99267	3.46896	V	3×180	0.8	1.03	>25.45
2007 Mar. 15.32476	598.7975	V	6×120	0.6	1.10	Reference
2005 Jul. 26.99009	2.46638	300V	3×600	1.1	1.03	Spectrum

of short GRB afterglows is still in its infancy, and only in a few cases are detailed observations available. Typically, the sampling of the afterglow light curves is poor and broad-band data are lacking, also due to the intrinsic faintness of these events (Berger et al. 2007). In general, the afterglows of short/hard GRBs have shown an overall similarity with those of their long-duration brethren, with power-law decays interrupted by breaks and flares. Basic quantities, however, are still poorly constrained, such as the true energy release. In fact, the degree of collimation of their ejecta is still largely unknown, due to the sparse sampling of afterglow light curves (e.g. Watson et al. 2006).

The *Swift* and HETE-2 results have also challenged the standard division of GRBs into two families based on duration and spectral hardness, fostering the search of new classification schemes (Donaghy et al. 2006; O'Brien & Willingale 2007; Zhang et al. 2007). Long-lasting (~100 s), soft emission following short GRBs was revealed, sometimes comprising a major fraction of the total fluence (Villasenor et al. 2005; Barthelmy et al. 2005; Norris & Bonnell 2006; Lazzati et al. 2001). A possible extreme example of this behavior is GRB 060614 (Gehrels et al. 2006; Zhang et al. 2007; Mangano et al. 2007), a long-duration GRB with deep limits on any associated supernova (Della Valle et al. 2006; Gal-Yam et al. 2006; Fynbo et al. 2006).

GRB 050724 (Covino et al. 2005) is one of the most interesting short/hard GRBs discovered so far. It was the second of this class with an optical and near-infrared (NIR) counterpart (Berger et al. 2005; D'Avanzo et al. 2005; Cobb & Bailyn 2005; Wiersema et al. 2005), and the first with detectable radio emission (Cameron & Frail 2005; Berger et al. 2005). It is also the prototype of short/hard GRBs with long-lasting soft emission (Barthelmy et al. 2005; Campana et al. 2006). The afterglow was found overlaid on a bright ($L \gtrsim L_*$) galaxy at redshift $z = 0.258$ with very low star formation (<0.05 $M_\odot$ yr^{-1}; Berger et al. 2005; Prochaska et al. 2006) and an old stellar population (>2.6 Gyr; Gorosabel et al. 2006). GRB 050724 currently is the best case for association between a GRB and an early-type galaxy.

We present here optical observations of the afterglow and host galaxy of GRB 050724. Our data, described in Sect. 2, nearly double the available dataset for this event. The afterglow and host galaxy are discussed in Sects. 3 and 4, respectively, and we comment on our results in Sect. 5. Throughout the paper, the decay and spectral indices α and β are defined by $F_\nu(t, \nu) \propto (t - t_0)^{-\alpha} \nu^{-\beta}$, where t_0 is the burst trigger time (2005 Jul 24.52371 UT). We assume a ΛCDM cosmology with $\Omega_{\rm m} = 0.27$, $\Omega_\Lambda = 0.73$ and $h_0 = 0.71$ (Spergel et al. 2003). At the GRB redshift ($z = 0.258$), the luminosity distance is 1.30 Gpc, the distance modulus is 40.56 mag, and 1″ corresponds to 3.97 kpc. All errors are at the 1σ confidence level unless stated otherwise.

2. Observations and data analysis

We observed the field of GRB 050724 with the ESO Very Large Telescope (VLT), using the FORS1 instrument, starting 0.5 days after the GRB. Imaging in the V, R and I bands was carried out during several of the subsequent nights. Table 1 provides a summary of our observations. Flux calibration was achieved by observing the Landolt standard field PG 1323−086 during several photometric nights. The zeropoint was found to be stable up to ≈0.02 mag. Inside the XRT error circle (Barthelmy et al. 2005), the bright galaxy first noted by Bloom et al. (2005) is clearly visible. From our late-time, best-seeing images, we measured its magnitudes to be $V = 20.45 \pm 0.01$, $R = 19.47 \pm 0.01$, and $I = 18.59 \pm 0.01$ mag (without any extinction correction). These values are ≈0.1 mag brighter than those reported by Gorosabel et al. (2006), which may reflect our ability to account for the low-surface brightness regions of the galaxy, or may simply be due to a calibration mismatch. For reference, we provide in Table 2 the magnitudes of a few stars in the GRB field which we adopted as secondary calibrators. Aperture photometry of the host galaxy revealed a clear dimming in all filters between the first and subsequent epochs, providing evidence of the presence of the fading afterglow. To obtain more accurate results, PSF-matched image subtraction was performed using the ISIS package (Alard & Lupton 1998). Late-time images with good seeing were adopted as templates for galaxy subtraction, yielding a detection of the afterglow in all filters at several epochs (Fig. 1). The afterglow flux was determined by comparison with that of artificial stars of known magnitude inserted in the original images. We expect little afterglow contribution in the reference images (<10%). We explicitly checked this in the R band, where we adopted two different reference images (≈5.5 and 32.5 days after the GRB; see Table 1), and obtained consistent results. Our final photometry is reported in Table 1, and supersedes our preliminary report (D'Avanzo et al. 2005).

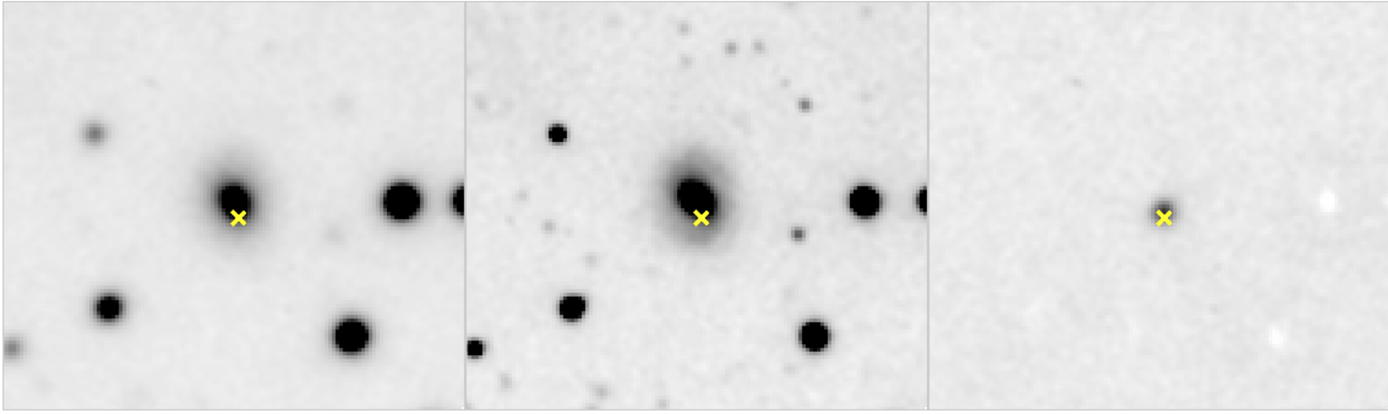

Fig. 1. *R*-band images of the field of GRB 050724 about 0.5 (*left*) and 5.6 (*middle*) days after the burst. The right panel gives the result of the subtraction, showing the optical afterglow in the first epoch. Each box is 26″ × 22″ wide. North is up and east is left. The cross marks the position of the radio afterglow (Berger et al. 2005).

Table 2. Magnitudes of reference stars in the field of GRB 050724.

RA (J2000)	Dec (J2000)	V	R	I
$16^h24^m44\overset{s}{.}12$	$-27°33'37\overset{''}{.}2$	18.74 ± 0.02	18.18 ± 0.01	17.64 ± 0.01
$16^h24^m38\overset{s}{.}73$	$-27°32'17\overset{''}{.}9$	20.01 ± 0.01	19.45 ± 0.01	18.82 ± 0.02
$16^h24^m44\overset{s}{.}74$	$-27°30'59\overset{''}{.}9$	19.71 ± 0.01	19.14 ± 0.01	18.59 ± 0.02

From the subtraction images, we could accurately determine the position of the afterglow, which was located at the coordinates RA = $16^h24^m44\overset{s}{.}38$, Dec = $-27°32'27\overset{''}{.}1$ (J2000, $0\overset{''}{.}35$ RMS error, relative to 300 USNO-B1 stars). These compare well with those of Berger et al. (2005), and are also consistent with the X-ray (Burrows et al. 2005a; Barthelmy et al. 2005) and radio (Soderberg 2005; Berger et al. 2005) positions. The afterglow is thus $0\overset{''}{.}6$ off the center of the host galaxy, which corresponds to 2.6 kpc in projection at $z = 0.258$.

Spectroscopy of the host galaxy was obtained during the night of 2006 Jul. 26, using a slit 1″ wide and the 300V grism (7.5 Å resolution), covering the 3800–9000 Å wavelength range. At that epoch the afterglow was only marginally contributing to the total light (<2%). Standard spectroscopic reduction was performed using IRAF[1]. The spectra were wavelength- and flux-calibrated by using a He-Ar lamp and observing the spectroscopic standard star LTT 6248. Slit losses were corrected for by matching the measured fluxes to the photometry. A simple rescaling by a factor of 2.3, independent of the wavelength, was enough to account for the difference. This correction is consistent with the angular size of the galaxy (half-light radius of $\approx 1\overset{''}{.}5$).

3. Afterglow properties

A collection from the literature of the optical and near-infrared photometry of the GRB 050724 afterglow reveals some discrepancies (≈0.5 mag) when comparing simultaneous data. This is not surprising, given the intrinsic difficulties involved in the image subtraction process, especially critical given the brightness of the host galaxy. Furthermore, several data taken from the GCN circulars[2] might suffer from a preliminary photometric calibration. Last, some of these measurements were computed adopting, as reference images for the subtraction, exposures relatively close in time to the GRB, and possibly contaminated by residual afterglow light. We note, however, that our first *I*-band point ($t - t_0 \approx 0.5$ days) is fully consistent with a contemporaneous measurement by Berger et al. (2005).

Figure 2 shows our measurements (filled symbols), together with those available from the literature (empty symbols). X-ray data from *Swift* (BAT and XRT) and *Chandra* (ACIS-S) were taken from Campana et al. (2006) and Grupe et al. (2006), respectively. Radio data[3] are from Berger et al. (2005). For self-consistency, we initially performed the fits using our data only. The afterglow is detected up to 3.5 days after the GRB. Assuming a power-law behavior, the decay slopes are $\alpha_I = 1.74 \pm 0.09$, $\alpha_R = 1.51 \pm 0.09$, and $\alpha_V > 1.38$ in the *I*, *R* and *V* bands, respectively. Fitting the whole dataset together, we obtain $\alpha_{\rm opt} = 1.64 \pm 0.06$ ($\chi^2_r = 3.2/2$). Berger et al. (2005) found a steeper slope $\alpha_K > 1.9$ in the *K* band. It is unclear whether this discrepancy has some physical significance, but we caution that few points are available, and that the light curve might not be represented by a pure power law (see below). Apart from the precise value, the decay index is quite steep, and this led Berger et al. (2005) to propose that the light curve had a break before the beginning of their observations (≈0.5 days after the GRB). The early UVOT *V*-band upper limit at $t - t_0 \approx 20$ min (Chester et al. 2005), coupled with our measurements, also implies a flatter decay at $t - t_0 \lesssim 0.5$ days (Fig. 2). If interpreted as a jet break, such a limit on the break time would imply a jet half-opening angle $\vartheta_{\rm jet} \lesssim 8.5°$ (Berger et al. 2005).

An inspection of the X-ray data (Fig. 2), however, suggests a different possibility. Similar to that observed in many long/soft GRBs (Tagliaferri et al. 2005; Nousek et al. 2006), the X-ray light curve shows a steep decay ($\alpha_X \approx 3.6$) which becomes flatter at ~800 s (Campana et al. 2006). From this time on, the decay can be described by a steadily declining component with flaring activity superimposed. Most noticeable is the large flare peaking at ~50 ks (observer frame time). If this flare is interpreted as being due to a different component (e.g., late activity from the central engine: Fan & Wei 2005a; Zhang et al. 2006; Perna et al. 2006; Proga et al. 2006; Dai et al. 2006; Lazzati & Perna 2007; Chincarini et al. 2007), the forward shock emission does

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of the Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[2] http://gcn.gsfc.nasa.gov

[3] http://www.aoc.nrao.edu/~dfrail/allgrb_table.shtml

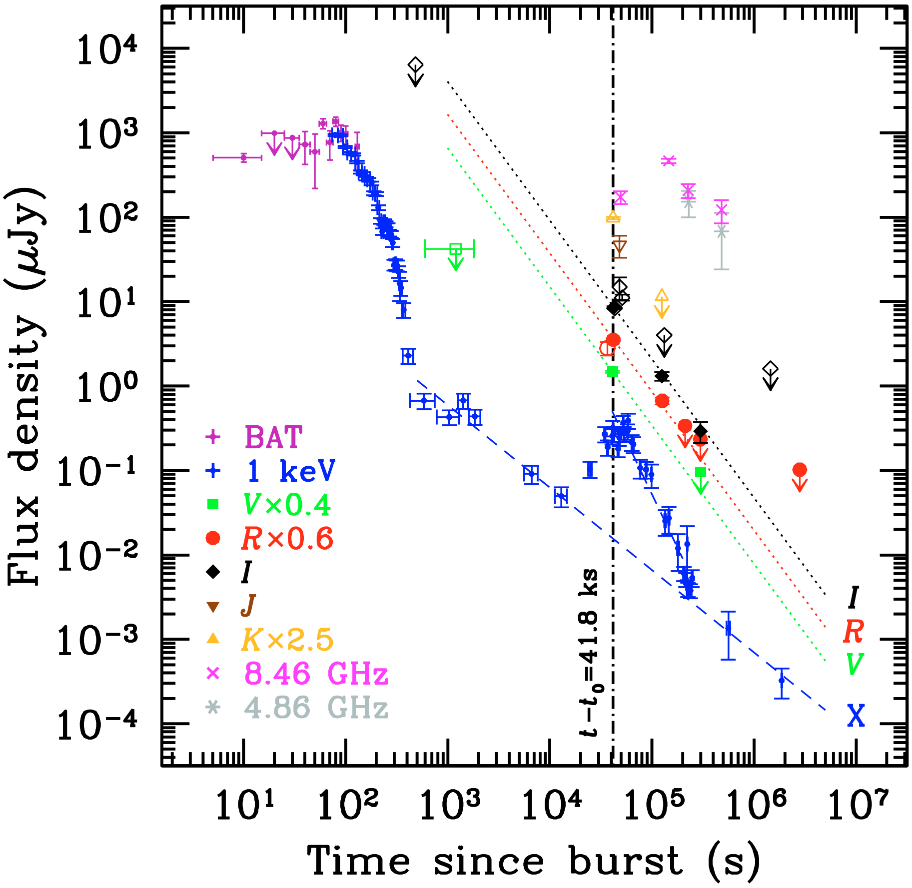

Fig. 2. X-ray, optical and radio light curves of the afterglow of GRB 050724. Filled and empty symbols represent measurements from our data and from the literature, respectively (Berger et al. 2005; Chester et al. 2005; Torii 2005; Cobb & Bailyn 2005; Wiersema et al. 2005; Pastorello et al. 2005). The V-, R- and K-band data have been displaced vertically for graphical purposes (see legend). No correction for optical extinction has been applied. The dotted and dashed lines show the best power-law fits to the optical and X-ray data, respectively. The vertical dot-dashed line marks the time at which we computed the SED (Fig. 3).

not show any break until at least ~3 weeks after the GRB. This would imply a low degree of collimation, with $\vartheta_{\rm jet} \gtrsim 25°$ (Grupe et al. 2006).

The discrepancy in the determination of the jet angle may be solved by considering that all the optical data were taken simultaneously with the large flare peaking at $t - t_0 \approx 50$ ks, which likely contributed in the optical band as well. The possible detection of a rising light curve ($F \propto t^{1.7}$) in the I band between 43 and 51 ks (Berger et al. 2005) provides some support for this hypothesis. To further test this possibility, we built the spectral energy distribution (SED) of the counterpart at 41.8 ks after the burst. This epoch was chosen because multiband data are available and because the afterglow was detected with high signal to noise (S/N) ratio. The major uncertainty is actually the level of the Galactic extinction, which is quite large towards this region of the sky ($l = 350°$, $b = +15°$). Furthermore, as pointed out by Vaughan et al. (2006), this line of sight passes close to the Ophiuchus molecular cloud complex, making the extinction curve and the dust-to-gas ratio uncertain. The maps by Schlegel et al. (1998) provide $E(B-V) = 0.61$ mag, but they are known to be scarcely accurate in highly extinguished regions. Dutra et al. (2003) have shown that, in this $E(B-V)$ range, the actual extinction is lower by a factor of 0.75, with a scatter of <20%. We therefore assume $E(B-V) = 0.46$ mag, bearing in mind the uncertainty associated with this value. For the X-ray spectral slope, we adopted $\beta_{\rm X} = 0.74 \pm 0.13$ (90% uncertainty), the average value reported by Campana et al. (2006) over the flare interval (which is consistent with the measurement by Grupe et al. 2006).

The resulting SED is shown in Fig. 3. With the assumed extinction, and using our VRI measurements together with the nearly simultaneous K-band detection by Berger et al. (2005), the optical spectral slope is $\beta_{\rm opt} = 0.78 \pm 0.07$. No extinction is assumed close to the burst explosion site, as expected for a galaxy with an old stellar population and in agreement with existing estimates (Gorosabel et al. 2006). Overall, the SED is consistent with a single power law extending from the optical to the X-ray ranges, as suggested by the similarity of $\beta_{\rm opt}$, $\beta_{\rm X}$, and the broad-band spectral index $\beta_{\rm OX} = 0.72 \pm 0.04$. We note that a perfect match would require $E(B-V) = 0.49$ mag, which is very similar to the adopted value and within the scatter of the correction proposed by Dutra et al. (2003). An optical rebrightening simultaneous with an X-ray flare was also proposed by Watson et al. (2006) for the short GRB 050709, again removing the need for a break to explain the steep optical decay. Small-amplitude wiggles have also been observed in the afterglows of the short GRB 060121 (de Ugarte Postigo et al. 2006) and GRB 060313 (Roming et al. 2006).

If the optical and X-ray data belong to the same component, we would expect the same temporal behavior in the two bands, while the decay in the optical is slower than in the X-rays ($\alpha_{\rm X} = 2.98 \pm 0.15$ during the flare decline). We note, however, that the optical slope we computed is likely to be underestimated. In fact, as reported by Berger et al. (2005), the optical flux was rising at the time of our first observation ($t - t_0 \approx 41.8$ ks), as in the X-rays. Therefore, since we do not know the optical peak time, and the light curve is poorly sampled, we can provide only a lower limit to the optical slope. To estimate the effect of this uncertainty, we took all the available I-band points, including those by Berger et al. (2005), and fitted only those taken at $t - t_0 > 50$ ks. In this case, we do indeed obtain a steeper value $\alpha_I = 2.27 \pm 0.14$. Finally, we note that the observed decay rates can be different in the two bands if the contribution from the underlying forward shock emission was different, especially at late times.

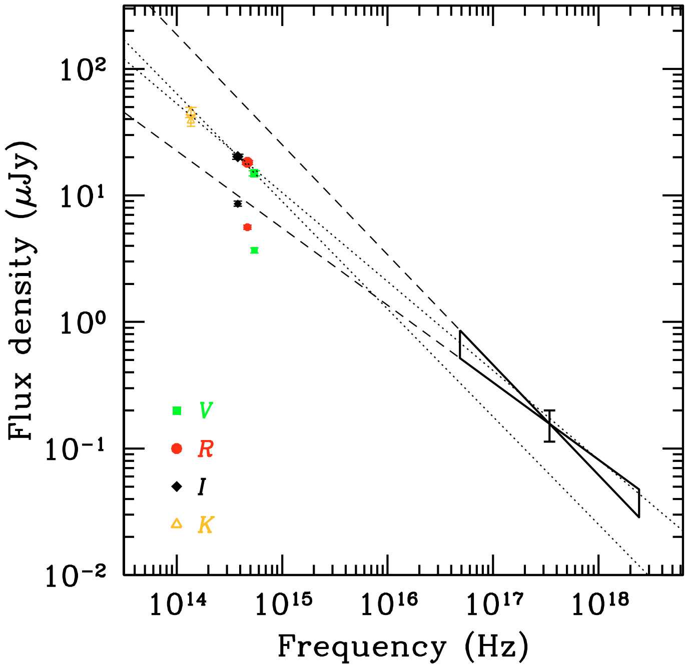

Fig. 3. Optical/X-ray SED at $t - t_0 = 41.8$ ks. Data were taken from our VLT images (V, R and I bands) and from Berger et al. (2005, K band). Small symbols show the observed fluxes, while the large ones indicate the values corrected for extinction in the Milky Way, assuming $E(B-V) = 0.46$ mag. The dotted and dashed lines show the extrapolation of the optical and X-ray spectra, respectively.

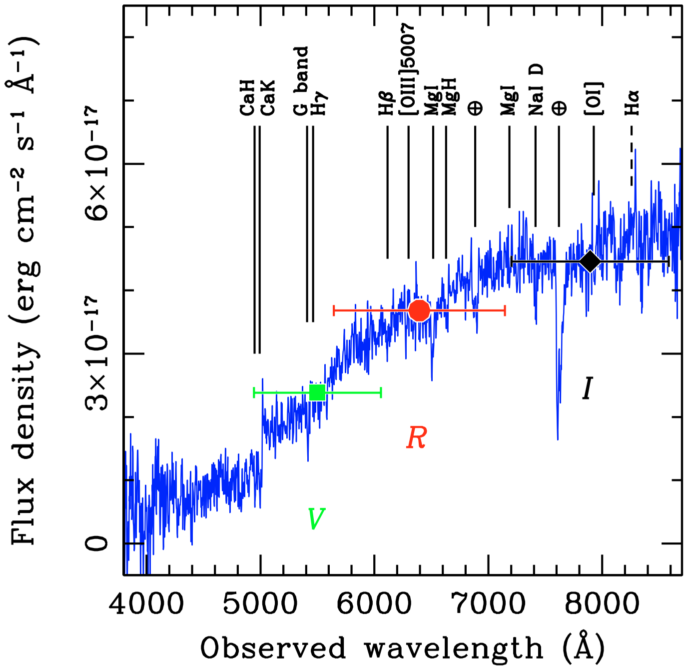

Fig. 4. Spectrum of the host galaxy of GRB 050724, taken on 2005 Jul. 26.99 UT with VLT+FORS1. Telluric lines are indicated by the symbol ⊕. The spectrum has been rescaled by a factor of 2.3 to match our photometric measurements (dots). In this plot, no extinction correction has been applied.

In Fig. 2 we also show the available radio measurements. A rebrightening is visible in this band too, at a time somehow delayed with respect to the X-rays. It is not clear whether these two components are related. Panaitescu (2006) explained the radio peak as being due to the passage of the forward shock injection frequency through the observed band. Similar behavior was observed in several other afterglows, and the flaring activity at high energy is not needed to explain the radio light curve.

3.1. The X-ray flare

By modeling a smaller data set, Panaitescu (2006) suggested that the cooling frequency was below the optical band at $t - t_0 = 0.5$ days. His analysis, however, assumed that the optical emission was due to the forward shock. Furthermore, he assumed a lower extinction $E(B-V) = 0.26$ mag (Burstein & Heiles 1982).

As discussed above, however, our data support a different interpretation, namely that the observed emission at 0.2–3 days was related to the large flare apparent in the X-ray light curve. Extensive studies have shown that such flares cannot be produced in the forward shock, but are the result of late-time activity of the GRB central engine (Burrows et al. 2005b; Zhang et al. 2006; Chincarini et al. 2007), possibly late internal shocks. Independent of the interpretation of the optical data, the hard X-ray spectral index (average $\beta \approx 0.74$) suggests that the peak energy E_p was above the XRT band during the flare. The location of E_p can be used to constrain the emission process, under the hypothesis that the flare was produced by synchrotron radiation in a late internal shock. Using Eq. (17) of Zhang & Mészáros (2002), we have

$$E_\mathrm{p} \sim 160 \xi L_{52}^{1/2} R_{13}^{-1}\ \mathrm{keV}, \quad (1)$$

where $L = 10^{52} L_{52}$ erg s^{-1} is the flare luminosity, $R = 10^{13} R_{13}$ cm is the emission radius, and ξ is a numerical coefficient dependent on the details of the emission process. By imposing $E_\mathrm{p} \gtrsim 5$ keV and using the measured isotropic luminosity $L_\mathrm{flare} = 6 \times 10^{44}$ erg s^{-1} (0.3–10 keV), we infer a radius $R_{13} \lesssim 0.01\xi$. For the fireball to be optically thin to Thomson scattering, furthermore, $R_{13} \gtrsim 1$ is required, and hence $\xi \gtrsim 100$. The parameter ξ is dependent upon a number of variables, and may be expressed as $\xi = \xi_0(\Gamma_{12} - 1)^\kappa$, where $\xi_0 < 1$, Γ_{12} is the relative Lorentz factor between the colliding shells, and $\kappa = 2$ or $\kappa = 2.5$ depending on the shock parameters (Zhang & Mészáros 2002). It is apparent that a large ξ can be obtained only if $\Gamma_{12} \gg 1$. The data, therefore, constrain $\Gamma_{12} \approx \Gamma_2/(2\Gamma_1) \gtrsim 10$.

This result has important consequences for the physics of the central engine. A large Γ_{12} implies that the impacting shell was emitted from the central engine long after the main burst, rather than simultaneously. In fact, if Δt is the time interval between the ejection of two shells, simple kinematic arguments (Lazzati et al. 1999) imply

$$t_\mathrm{flare} \approx (1+z)\frac{4\Gamma_{12}^2}{4\Gamma_{12}^2 - 1}\Delta t. \quad (2)$$

When $\Gamma_{12} \gg 1$, $\Delta t \approx t_\mathrm{flare}/(1+z) = 40$ ks. This result, based on the spectral properties of the flare, agrees with that inferred by studying flare light curves (Lazzati & Perna 2007).

4. The host galaxy

We secured photometric and spectroscopic observations of the host galaxy of GRB 050724 to assess the nature of the GRB progenitor environment. Our spectrum is shown in Fig. 4, and is typical of an evolved galaxy with an old stellar population. The colors are consistent with those measured by

Gorosabel et al. (2006), which found a best-fit age larger than 2.6 Gyr for the dominant stellar population. In the spectrum, no emission features are detected, but from several absorption lines (Table 3) we could measure a redshift $z = 0.2582 \pm 0.0003$. This is consistent with previous determinations (Berger et al. 2005; Prochaska et al. 2006). We also provide an upper limit to the Hα luminosity, $L < 2.8 \times 10^{40}$ erg s^{-1} (3σ, corrected for slit losses and Galactic extinction). Following Kennicutt (1998), this corresponds to a star formation rate (SFR) $< 0.17\ M_\odot$ yr^{-1}. The absolute magnitude of the galaxy is $M_B = -21.2$ ($L \approx 1.2\ L_*$ assuming $M_B^* = -21$), computed from the measured V-band flux, so that the SFR per unit luminosity is $<0.14\ M_\odot$ yr^{-1} L_*^{-1}. This limit is $\sim$50 times lower than the average value found in long-duration GRB hosts, both at low and intermediate redshift (Sollerman et al. 2005; Christensen et al. 2004). From the available spectrum, we could also compute a rough estimate of the metallicity, based on the Mg_2 index. Using the theoretical prescription by Buzzoni et al. (1992), and adopting the age of 2.6 Gyr as determined by Gorosabel et al. (2006), we infer [Fe/H] $\approx$ 0.1. Another estimate was obtained using the G band, Hβ, Mg_2, and Na I indices and the empirical relations by Covino et al. (1995). A correction is necessary to account for the age difference between the GRB host galaxy and the Galactic globular clusters, against which the empirical relations are calibrated. The inferred metallicity is roughly solar (with an uncertainty of $\approx$0.2 dex), which is larger than that usually observed for long GRB hosts (e.g. Savaglio 2006; Sollerman et al. 2005; Stanek et al. 2006). We caution, however, that our determination of the metallicity is appropriate for the stellar component, while the values inferred for long GRB hosts are relative to the interstellar medium.

The host galaxy of GRB 050724 has been morphologically classified as an elliptical galaxy (e.g Berger et al. 2005). Figure 5 shows an R-band image taken under very good-seeing conditions ($0\farcs5$) on 2006 July 30.1 UT. The bulge is clearly prominent, but some faint structures are apparent towards north-west and, to a lesser extent, to the south. These may be due to weak spiral arms. The galaxy may thus be classified morphologically as an Sa spiral. To perform a more quantitative analysis, we studied its spatial profile adopting a two-dimensional fitting approach, applied to our late-time best-seeing images. To perform the fit we used the image decomposition program GALFIT (Peng et al. 2002), a package designed to accurately model galaxy profiles, combining simultaneously an arbitrary number of profiles. The fitting algorithm constructs a model image, convolves it with the point-spread function (PSF), and finally compares the result with the data. During the fit, the reduced χ^2 is minimized using a Levenberg-Marquardt algorithm. The uncertainties used to calculate the reduced χ^2 as a function of the pixel position are the Poisson errors, which are generated on the basis of the known detector characteristics. For each band we constructed the PSF by identifying in the images 10 point sources and averaging them. The initial guesses for the parameters (magnitude, scale length, position angle and minor to major axis ratio) were obtained by running SExtractor (Bertin & Arnouts 1996).

A pure elliptical profile is not a good description for the galaxy morphology. For L_* galaxies, the surface brightness profile is usually described by the de Vaucouleurs $r^{1/4}$ law. When applying this model, the residual images clearly show the spiral arm structure in all the bands, confirming the results of visual inspection. We allowed for a more general profile function, namely a Sersic model with free index n, but we saw only marginal improvement. The best-fit index $n = 2.8$ (computed in the R and I bands) is moreover typical of low-luminosity ellipticals (e.g. Caon et al. 1993), unlike the host of GRB 050724 (which has $L > L_*$). A successful description of the galaxy was obtained by combining three different components: a de Vaucouleurs profile, an exponential (disk) function, and a Sersic component. The best-fit values for the morphological parameters are reported in Table 4. The V-band image has a lower S/N ratio, so we list only the results for the R and I bands.

5. Discussion

We have presented an extensive observational campaign characterizing the afterglow and host galaxy of the short/hard GRB 050724. We have provided new data to feed the models and better understand the physical processes occuring in short GRB fireballs. It is noteworthy that short/hard GRB afterglows share common properties with those of the long-duration events (see Nakar 2007 for a recent review). For example, independent of the dust extinction, our data (Fig. 3) show that the optical spectrum has the typical power-law shape predicted by the synchrotron model.

Based on the existing data, we propose that the steep decay observed in the optical light curve of the GRB 050724 afterglow did not result from jetted emission, but was due to the large X-ray flare which was contributing to the optical band as well. Such prominent flares are not common, although not unprecedented (e.g. GRB 070311: Kann 2007; Guidorzi et al. 2007). These large flares provide a good opportunity to study GRB physics. In particular, if indeed they are due to late internal activity, they might show measurable polarization (Fan et al. 2005b) on a timescale easily accessible to large telescopes. The interpretation of the optical data as belonging to the flare has important consequences in terms of the energetics of the burst. The low collimation degree inferred from the X-ray light curve ($\vartheta_{\rm jet} \gtrsim 25°$) implies that the actual explosion energy was not much lower than the isotropic-equivalent value (4×10^{50} erg; Barthelmy et al. 2005). This is comparable to the typical (beaming-corrected) energy release of long-duration GRBs (Frail et al. 2001; Ghirlanda et al. 2007). Collimation estimates also affect the computation of short GRB rates (Nakar et al. 2006; Guetta & Piran 2006). To date, the best evidence of a jetted geometry in short GRBs is provided by the breaks in the X-ray light curves of GRB 051221A (Burrows et al. 2006; Soderberg et al. 2006) and GRB 061201 (Stratta et al. 2007), although no late optical and radio data are available to test the broad-band behavior[4]. In the latter case, a very early break was detected with properties in good agreement with the expectations of the jet model. Albeit that the redshift of this GRB is unknown, current limits constrain the beaming-corrected energy to be less than 10^{49} erg, in turn showing that the short GRB luminosity function is quite broad.

An alternative possibility to explain the different behavior in the optical and X-ray bands is to assume that the X-ray emission was powered by a different, long-lived component, as recently suggested for long-duration GRBs (Panaitescu et al. 2006; Willingale et al. 2007; Uhm & Beloborodov 2007; Genet et al. 2007; Ghisellini et al. 2007). The consistency of the optical/X-ray SED would in this case be fortuitous.

Flares in the light curves of both short and long GRBs have been attributed to late internal shocks (Fan & Wei 2005a; Zhang et al. 2006). There are two variants of this model. In the first, the colliding shells are ejected together with the main burst, and

[4] The long-duration GRB 060614, one of the best cases for an achromatic break in any GRB (Mangano et al. 2007), might be related to the short burst category, but the classification is not conclusive (Gehrels et al. 2006; Zhang et al. 2007).

Table 3. Absorption lines in the spectrum of the host galaxy of GRB 050724. Features marked with an asterisk * have low significance and were not used for the redshift computation. The line equivalent widths are in the observer frame.

Line	λ (rest) (Å)	λ (observed) (Å)	Redshift	EW (Å)
Ca K	3933.7	4950.9	0.2586	5.4
Ca H	3968.5	4995.2	0.2587	4.8
G band	4299.6	5416.3	0.2597	4.4
$H\gamma^*$	4340.5	5469.7	0.2602	0.8
$H\beta$	4861.3	6113.0	0.2575	0.8
[O III]*	5006.8	6300.8	0.2584	0.5
Mg I	5172.7	6504.0	0.2574	3.3
Mg I	5183.7	6516.0	0.2570	1.6
MgH*	5269.0	6643.5	0.2609	1.1
MgI	5711.1	7182.8	0.2577	0.9
Na I D	5890.9	7413.1	0.2584	1.0
Na I D	5895.9	7420.1	0.2585	1.5
[O I]*	6300.0	7931.7	0.2590	2.2

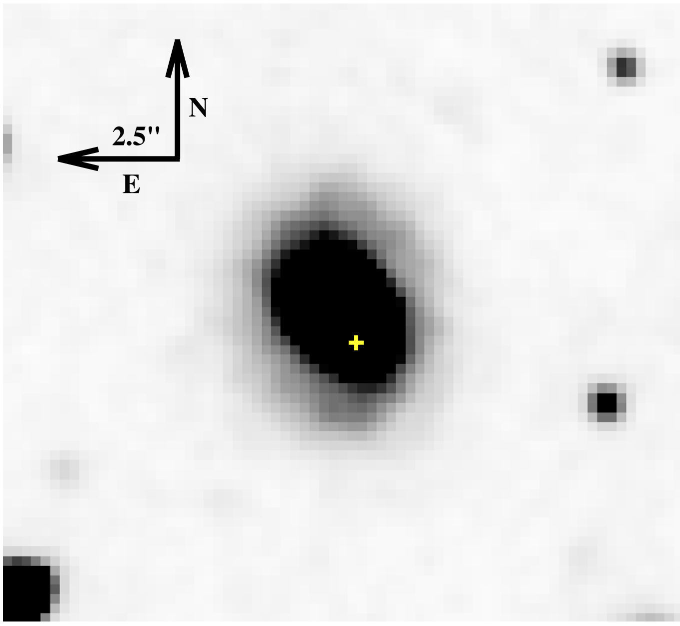

Fig. 5. Close-up on the host galaxy of GRB 050724. The image was taken in the R band with VLT+FORS1 on 2005 Jul. 30.1 UT. The cross marks the position of the optical afterglow. Extended emission is visible towards north-west and to the south of the galaxy. The intensity scale is non linear to enhance the faint peripheral regions.

impact each other at late times because they a have small velocity spread. In the second case, the central engine remains active for a long time and emits fast shells at late times. The X-ray flare of GRB 050724 was spectrally hard, with the peak energy above the XRT range. In order to yield such a high value, the Lorentz factor contrast of the colliding shells had to be large. This in turn implies that the central engine remained active for a long time (≈40 ks), which is not straightforward to achieve in short GRB models (see Lee & Ramirez-Ruiz 2007, for a review).

GRB 050724 is also remarkable for its association with a galaxy having an old population. Following the discovery of several short GRB host galaxies, it has become apparent that this population includes objects with different properties, and that a significant fraction of short GRBs explode inside systems with moderate ongoing star formation and relatively young stellar populations (Fox et al. 2005; Covino et al. 2006;

Table 4. Two-dimensional morphological fit parameters of the host galaxy of GRB 050724. An asterisk * denotes a frozen quantity. From top to bottom: the Sersic index n, the scale radius r_0, the ratio of the semi-minor to semi-major axis b/a, and the position angle PA (measured counterclockwise relative to the north).

Parameter	Band	De Vaucouleurs	Exponential	Sersic
n	I	4*	1*	1.22
	R	4*	1*	1.12
r_0 (″)	I	1.56	1.08	1.74
	R	1.54	1.09	1.12
b/a	I	0.784	0.784	0.513
	R	0.789	0.814	0.867
PA (°)	I	23.85	23.85	40.20
	R	24.46	23.40	21.01

Berger et al. 2007; D'Avanzo et al. 2007, in preparation). GRB 050724 provides the most compelling evidence to date that short GRBs also occur inside galaxies with negligible ongoing star formation. Using the formulation outlined by Bloom et al. (2002), we estimated the probability P to find a galaxy brighter than the candidate host[5] ($R = 18.2$) at an angular distance less than 0.″6 from the optical afterglow. We found P to be as low as 6.3×10^{-5} (see also Barthelmy et al. 2005), confirming that the association is not due to a chance superposition. It has been suggested that other short GRBs are associated with early-type galaxies, most noticeably GRB 050509B (Gehrels et al. 2005; Hjorth et al. 2005b; Bloom et al. 2006). In terms of progenitors, this implies that either more than one evolutionary channel leads to the production of short GRBs, or that there is a wide distribution of delay times between the birth of the progenitor system and the GRB explosion (Nakar et al. 2006; Guetta & Piran 2006; Zheng & Ramirez-Ruiz 2007). The inferred scenario is broadly consistent with models involving the merging of a binary compact object system (Eichler et al. 1989; Belczynski et al. 2006). The old age of the host galaxy of GRB 050724 is also consistent with the lack of detection of a supernova (SN) associated with this GRB. Our late-time images (32 days after the GRB) constrain the contribution of a SN at the position of the GRB to be fainter than SN 1998bw (Galama et al. 1998) by at least ≈3 mag in the observed R band. This corresponds to an absolute magnitude $M_V > -16.2$.

The association of GRB 050724 with an early-type galaxy is especially significant given its peculiar prompt light curve shape (a short spike followed by a long, soft pulse), which would nominally make GRB 050724 a long-duration event (formally $T_{90} > 2$ s; Barthelmy et al. 2005). Its host galaxy is in fact distinctly different from those of long GRBs (which are typically blue, subluminous, young and metal-poor; e.g. Djorgovski et al. 1998; Le Floc'h et al. 2003; Fynbo et al. 2003; Christensen et al. 2004; Fruchter et al. 2006), and is very unlikely to host young stars akin to the progenitors of long GRBs. This supports the idea that the duration is not the only parameter relevant to the classification of bursts, and that some long-lasting GRBs are not associated with star formation (see also Zhang et al. 2007). Late-time (≈100 s) soft emission occurs in a significant fraction of short bursts, ≈30% in the *Swift*/HETE-2 sample. This is actually a lower limit, since some of these events might be confused with long-duration events (e.g. GRB 050911: Page et al. 2006). There seems to be no relation between the host

[5] We applied the Galactic extinction correction $A_R = 1.2$ mag to the observed value, since galaxy counts are performed in low-extinction sky regions.

galaxy type and the presence of the soft component. A well-known case is GRB 050709 (Villasenor et al. 2005; Fox et al. 2005; Covino et al. 2006), exploded in a moderately star-forming galaxy, which also displayed the soft hump. Looking at the present sample, it seems that bursts with long-lasting emission have more often an optical afterglow (≈70% of the cases) than the overall population, but this is based on very limited statistics (seven events). Estabilishing the link between the different kinds of short-duration GRBs will be an important clue to understand their progenitors.

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References

Alard, C., & Lupton, R. H. 1998, ApJ, 503, 325
Barthelmy, S. D., Chincarini, G., Burrows, D. N., et al. 2005, Nature, 438, 994
Belczynski, K., Perna, R., Bulik, T., et al. 2006, ApJ, 648, 1110
Berger, E., Price, P. A., Cenko, S. B., et al. 2005, Nature, 438, 988
Berger, E., Fox, D. B., Price, P. A., et al. 2007, ApJ, 664, 1000
Bertin, E., & Arnout, S. 1996, A&AS, 117, 393
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Bloom, J. S., Dupree, A., Chen, H.-W., & Prochaska, J. X. 2005, GCN Circ., 3672
Bloom, J. S., Prochaska, J. X., Pooley, D., et al. 2006, ApJ, 638, 354
Burrows, D. N., Grupe, D., Kouveliotou, C., et al. 2005a, GCN Circ., 3697
Burrows, D. N., Romano, P., Falcone, A., et al. 2005b, Science, 309, 1833
Burrows, D. N., Grupe, D., Capalbi, M., et al. 2006, ApJ, 653, 468
Burstein, D., & Heiles, C. 1982, AJ, 87, 1165
Buzzoni, A., Gariboldi, G., & Mantegazza, L. 1992, AJ, 103, 1814
Cameron, P. B., & Frail, D. A. 2005, GCN Circ., 3676
Campana, S., Tagliaferri, G., Lazzati, D., et al. 2006, A&A, 454, 113
Caon, N., Capaccioli, M., & D'Onofrio, M. 1993, MNRAS, 265, 1013
Castro-Tirado, A. J., de Ugarte Postigo, A., Gorosabel, J., et al. 2005, A&A, 439, L15
Chester, M., Covino, S., Schady, P., Roming, P., & Gehrels, N. 2005, GCN Circ., 3670
Chincarini, G., Moretti, A., Romano, P., et al. 2007, ApJ, in press [arXiv:astro-ph/0702371]
Christensen, L., Hjorth, J., & Gorosabel, J. 2004, A&A, 425, 913
Cobb, B. E., & Bailyn, C. D. 2005, GCN Circ., 3694
Covino, S., Galletti, S., & Pasinetti, L. E. 1995, A&A, 303, 79
Covino, S., Antonelli, L. A., Romano, P., et al. 2005, GCN, Circ., 3665
Covino, S., Malesani, D., Israel, G. L., et al. 2006, A&A, 447, L5
Dai, Z. G., Wang, X. Y., Wu, X. F., & Zhang, B. 2006, Science, 311, 1127
D'Avanzo, P., Covino, S., Antonelli, L. A., et al. 2005, GCN Circ., 3690
Della Valle, M., Chincarini, G., Panagia, N., et al. 2006, Nature, 444, 1050
De Ugarte Postigo, A., Castro-Tirado, A. J., Guziy, S., et al. 2006, ApJ, 648, L89
Dezalay, J. P., Barat, C., Talon, R., et al. 1991, in Gamma-ray bursts, ed. W. Paciesas, & G. J. Fishman, AIP Conf. Proc. 265, 304
Djorgovski, S. G., Kulkarni, S. R., Bloom, J. S., et al. 1998, ApJ, 508, L17
Donaghy, T. Q., Lamb, D. Q., Sakamato, T., et al. 2006, ApJ, submitted [arXiv:astro-ph/0605570]
Dutra, C. M., Ahumada, A. V., Clariá, J. J., Bica, E., & Barbuy, B. 2003, A&A, 408, 287
Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Nature, 340, 126
Fan, Y. Z., & Wei, D. M. 2005a, MNRAS, 364, L42
Fan, Y. Z., Zhang, B., & Proga, D. 2005b, ApJ, 635, L129
Ferrero, P., Sanchez, S. F., Kann, D. A., et al. 2006, AJ, submitted [arXiv:astro-ph/0610255]
Fox, D. B., Frail, D. A., Price, P. A., et al. 2005, Nature, 437, 845
Frail, D. A., Kulkarni, S. R., Sari, R., et al. 2001, ApJ, 562, L55
Fruchter, A. S., Levan, A. J., Strolger, L., et al. 2006, Nature, 441, 463
Fynbo, J. P. U., Jakobsson, P., Møller, P., et al. 2003, A&A, 406, L63
Fynbo, J. P. U., Watson, D., Thöne, C. C., et al. 2006, Nature, 444, 1047
Galama, T. J., Vreeswijk, P. M., van Paradijs, J., et al. 1998, Nature, 395, 670
Gal-Yam, A., Fox, D. B., Price, P. A., et al. 2006, Nature, 444, 1053
Gehrels, N., Chincarini G., Giommi, P., et al. 2004, ApJ, 611, 1005
Gehrels, N., Sarazin, C. L., O'Brien, P. T., et al. 2005, Nature, 437, 851
Gehrels, N., Norris, J. P., Barthelmy, S., et al. 2006, Nature, 444, 1044
Genet, F., Daigne, F., & Mochkovitch, R. 2007, [arXiv:astro-ph/0701204]
Ghisellini, G., Ghirlanda, G., Nava, L., & Firmani, C. 2007, ApJ, 658, L75
Ghirlanda, G., Nava, L., Ghisellini, G., & Firmani, C. 2007, A&A, 466, 127
Gorosabel, J., Castro-Tirado, A. J., Guziy, S., et al. 2006, A&A, 450, 87
Guetta, D., & Piran, T. 2006, A&A, 453, 823
Grupe, D., Burrows, D. N., Patel, S. K., et al. 2006, ApJ, 653, 462
Guidorzi, G., Vergani, S. D., Sazonov, S., et al. 2007, A&A, in press [arXiv:0708:1383]
Hjorth, J., Watson, D., Fynbo, J. P. U., et al. 2005a, Nature, 437, 895
Hjorth, J., Sollerman, J., Gorosabel, J., et al. 2005b, ApJ, 630, L117
Kann, D. A. 2007, GCN Circ., 6209
Kennicutt, R. C. 1998, ARA&A, 36, 189
Kouveliotou, C., Meegan, C. A., Fishman, G. J., et al. 1993, ApJ, 541, L101
La Parola, V., Mangano, V., Fox., D., et al. 2006, A&A, 454, 753
Lazzati, D., & Perna, R. 2007, MNRAS, 375, L46
Lazzati, D., Ghisellini, G., & Celotti, A. 1999, MNRAS, 309, L13
Lazzati, D., Ramirez-Ruiz, E., & Ghisellini, G. 2001, A&A, 379, L39
Lee, W. H., & Ramirez-Ruiz, E. 2007, New J. Phys., 9, 17
Le Floc'h, E., Duc, P. A., Mirabel, I. F., et al. 2003, A&A, 400, 499
Levan, A. J., Tanvir, N. R., Fruchter, A. S., et al. 2006, ApJ, 648, L9
Mangano, V., Holland, S. T., Malesani, D., et al. 2007, A&A, 470, 105
Nakar, E. 2007, Phys. Rep., 442, 166
Nakar, E., Gal-Yam, A., & Fox, D. B. 2006, ApJ, 650, 281
Norris, J. P., & Bonnell, J. T. 2006, ApJ, 643, 266
Nousek, J. A., Kouveliotou, C., Grupe, D., et al. 2006, ApJ, 642, 389
O'Brien, P. T., & Willingale, R. 2007, Phil. Trans. R. Soc. A, 365, 1179
Page, K. L., King, A. R., Levan, A. J., et al. 2006, ApJ, 637, L13
Panaitescu, A. 2006, MNRAS, 367, L42
Panaitescu, A., Mészáros, P., Burrows, D., et al. 2006, MNRAS, 369, 2059
Pastorello, A., Kawabata, K., Pian, E., et al. 2005, GCN Circ., 3892
Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H. 2002, AJ, 124, 266
Perna, R., Armitage, P. J., & Zhang, B. 2006, ApJ, 636, L29
Prochaska, J. X., Bloom, J. S., Chen H.-W., et al. 2006, ApJ, 642, 989
Proga, D., & Zhang, B. 2006, MNRAS, 370, L61
Ricker, G. R., Atteia, J.-L., Crew, G. B., et al. 2002, in Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop Celebrating the First Year of the HETE Mission, ed. G. R. Ricker, & R. K. Vanderspek, AIP Conf. Proc. 662, 3
Roming, P. W. A., Vanden Berk, D., Pal'shin, V., et al. 2006, ApJ, 651, 985
Savaglio, S. 2006, New J. Phys., 8, 195
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Soderberg, A. M. 2005, GCN Circ., 3696
Soderberg, A. M., Berger, E., Kalsiwal, M., et al. 2006, ApJ, 650, 261
Sollerman, J., Östlin, G., Fynbo, J. P. U., et al. 2005, New A, 11, 103
Spergel, D. N., Verde, L., Peiris, H., et al. 2003, ApJS, 148, 175
Stanek, K. Z., Gnedin, O. Y., Beacom, J. F., et al. 2006, Acta Astron., 56, 333
Stratta, G., D'Avanzo, P., Piranomonte, S., et al. 2007, A&A, submitted
Tagliaferri, G., Goad, M., Chincarini, G., et al. 2005, Nature, 436, 985
Torii, K. 2005, GCN Circ., 3674
Uhm, Z. L., & Beloborodov, A. M. 2007, ApJ, 665, L93
Vaughan, S., Willingale, R., Romano, P., et al. 2006, ApJ, 639, 323
Villasenor, J. S., Lamb, D. Q., Ricker, G. R., et al. 2005, Nature, 437, 855
Watson, D., Hjorth, J., Jakobsson, P., et al. 2006, A&A, 454, L123
Wiersema, K., Rol, E., Starling, R., et al. 2005, GCN Circ., 3699
Willingale, R., O'Brien, P. T., Osborne, J. P., et al. 2007, ApJ, 662, 1093
Zhang, B., & Mészáros, P. 2002, ApJ, 581, 1236
Zhang, B., Fan, Y.-Z., Dyks, J., et al. 2006, ApJ, 642, 354
Zhang, B., Zhang, B.-B., Liang, E.-W., et al. 2007, ApJ, 655, L25
Zheng, Z., & Ramirez-Ruiz, E. 2007, ApJ, 665, 1220