Constraints on an optical afterglow and on supernova light following the short burst GRB 050813

P. Ferrero, S. F. Sanchez, D. A. Kann, S. Klose, J. Greiner, J. Gorosabel, D. H. Hartmann, A. A. Henden, P. Möller, E. Palazzi, A. Rau, B. Stecklum, A. J. Castro-Tirado, J. P. U. Fynbo, J. Hjorth, P. Jakobsson, C. Kouveliotou, N. Masetti, E. Pian, N. R. Tanvir, R. A. M. J. Wijers

ABSTRACT

1Thüringer Landessternwarte Tautenburg, Sternwarte 5, D–07778 Tautenburg, Germany
2Centro Astronómico Hispano Alemán de Calar Alto, Calle Jesus Durban Remon 2-2, E–04004 Almería, Spain
3Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstraße, D–85741 Garching, Germany
4Instituto de Astrofísica de Andalucía (IAA-CSIC), Apartado de Correos, 3.004, E–18.080 Granada, Spain
5Clemson University, Department of Physics and Astronomy, Clemson, SC 29634-0978, USA
6U. S. Naval Observatory/Universities Space Research Association, Flagstaff Station, Flagstaff, AZ 86001, USA
7European Southern Observatory, Karl Schwarzschild-Strasse 2, D–85748 Garching bei München, Germany
8INAF – Istituto di Astrofisica Spaziale e Fisica Cosmica di Bologna, via Gobetti 101, I-40129 Bologna, Italy
9Division of Physics, Mathematics and Astronomy, 105-24, California Institute of Technology, Pasadena, CA 91125
10Dark Cosmology Centre, Niels Bohr Insitute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen, Denmark
11Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield, Herts, AL10 9AB, UK
12NSSTC, SD-50, 320 Sparkman Drive, Huntsville, AL 35805, USA
13INAF – Osservatorio Astronomico di Trieste, Via Tiepolo 11, I-34143 Trieste, Italy
14Department of Physical and Astronomy, University of Leicester, Leicester, LE1 7RH, UK
15University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
We report early follow-up observations of the error box of the short burst 050813 using the telescopes at Calar Alto and at Observatorio Sierra Nevada (OSN), followed by deep VLT/FORS2 $I$-band observations obtained under very good seeing conditions 5.7 and 11.7 days after the event. Neither a fading after-glow, nor a rising SN component was found, so the potential GRB host galaxy has not been identified based on a comparison of the two VLT images taken at different epochs. We discuss if any of the galaxies present in the original 10 arcsec XRT error circle could be the host. In any case, the optical afterglow of GRB 050813 was of very low luminosity. We conclude that all these properties are consistent with the binary compact merger hypothesis for the progenitor of GRB 050813.

Subject headings: Gamma rays: bursts: individual: GRB 050813 — Supernovae: general

1. Introduction

1.1. Short Bursts

Much progress is currently being made toward understanding the nature of the progenitors responsible for the class of short-duration, hard gamma-ray bursts (Kouveliotou et al. 1993, see also Appendix B). While the physical link between long-duration, soft gamma-ray bursts and the core collapse of massive stars (e.g., Paczyński 1998) has been conclusively confirmed by the spectroscopic detection of supernova (SN) light following some bursts (Stanek et al. 2003; Hjorth et al. 2003; Pian et al. 2006; Woosley & Bloom 2006, for a review), the nature of the sources responsible for short bursts remains to be revealed in full. Although there is a developing consensus in the community that at least some short bursts are due to merging compact stellar objects (cf. Fryer, Woosley & Hartmann 1999; Aloy, Janka & Müller 2005; Rosswog 2005; Oechslin & Janka 2006; Faber et al. 2006), an unambiguous observational verification of this model is not an easy task and has not yet been accomplished. Furthermore, the origin of a certain fraction of short bursts as giant flares of magnetars in nearby galaxies seems to be possible as well (cf. Tanvir et al. 2005). Indeed,

---

1Based on observations collected at the European Southern Observatory, La Silla and Paranal, Chile (ESO Programme 075.D-0415) and on observations taken at the German-Spanish Calar Alto Observatory and at IAA’s Observatorio de Sierra Nevada in Spain.
the short-hard burst 051103 detected by the Interplanetary Network (Golenetskii et al. 2005) might be the first well-localized member of this class (Frederiks et al. 2007; Ofek et al. 2006).

Within the context of the merger model, the stellar populations underlying short bursts could be associated either with an old stellar population or even with a young one (Belczynski et al. 2006). Short bursts might therefore occur in quiescent ellipticals or star-forming galaxies. Indeed, the first short burst well-localized by Swift, GRB 050509B (Gehrels et al. 2005), was associated with a giant elliptical galaxy located in a cluster of galaxies at $z = 0.225$ (Bloom et al. 2006; Pedersen et al. 2005), while the HETE-2 short burst GRB 050709 (Hjorth et al. 2005b) occurred in an isolated, star-forming dwarf galaxy. Shortly thereafter GRB 050724 was found in association with a lone early-type galaxy (Bloom et al. 2005; Prochaska et al. 2005; Berger et al. 2005a; Gorosabel et al. 2006). Assuming as a working definition that a short burst should have $T_{90} < 2$ s, then since GRB 050813 six further short bursts have been accurately localized by HETE-2 or Swift via their X-ray afterglows by the end of September 2006 (see also table 8 in Donaghy et al. 2006). Among them GRB 051210 (La Parola et al. 2006), GRB 060502B (Bloom et al. 2007) and GRB 060801 (Racusin et al. 2006) had only X-ray afterglows, while GRB 051221A (Soderberg et al. 2006), GRB 060121 (Malesani et al. 2006; Levan et al. 2006; de Ugarte Postigo et al. 2006) and GRB 060313 (Roming et al. 2006; Hjorth et al. 2007, in preparation) have detected optical afterglows as well. A broad range of morphological types of host galaxies was derived for this set. For example, Bloom et al. (2007) postulated an association between GRB 060502B and a bright elliptical galaxy at a large offset at $z = 0.287$, while GRB 051221A is associated with an isolated star-forming dwarf galaxy (Soderberg et al. 2006), and the host of GRB 060121 might be a dusty edge-on irregular or spiral galaxy (Levan et al. 2006). This “mixed-bag” of host types is consistent with the idea that merging compact binaries will sample all types of galaxies, even those in which star formation turned off a long time ago. The short burst GRB 050813 belongs to the small set of short bursts for which up to date it has not been possible to define precisely the host galaxy.

1.2. GRB 050813

According to its observed duration ($T_{90}$, see below), GRB 050813 can be associated with the class of short bursts with very high (99.9%) probability (Donaghy et al. 2006). In addition, its measured spectral lag is consistent with zero, another important property of short bursts (Norris & Bonnell 2006; Donaghy et al. 2006). Furthermore, the small original Swift XRT error circle encompasses parts of an anonymous cluster of galaxies with ellipticals inside and close to the error circle (Gladders et al. 2005; Gorosabel et al. 2005; Prochaska et al. 2005).
Taken together, these observations suggest that GRB 050813 should be considered as a typical short burst.

GRB 050813 was detected by the Swift satellite on 2005 August 13, 6:45:09.76 UT (Retter et al. 2005). Its duration in the 15-350 keV band was 0.6 ± 0.1 seconds (Sato et al. 2005), making it after GRB 050509B and 050724 the third short burst that Swift localized quickly and precisely. It is reminiscent of GRB 050509B, which had a very faint X-ray afterglow (Gehrels et al. 2005). Ground analysis of the X-ray data revealed a faint, uncatalogued source at coordinates RA, DEC (J2000) = 16° 07′ 57.0″, +11° 14′ 52″ with an uncertainty of 10 arcsec radius (Morris et al. 2005). This position was later refined by Moretti et al. (2006) to RA, DEC (J2000) = 16° 07′ 57.07″, +11° 14′ 54.2″ with an uncertainty of 6.5 arcsec radius; an even smaller error region was reported by Prochaska et al. (2006). No optical or near-infrared afterglow candidate was found. Li (2005) reported an unfiltered upper limit of magnitude 18.6 at 49.2 seconds after the burst. UVOT observations started 102 seconds after the trigger and a 3-sigma upper limit of $V = 19.1$ was derived from a 188 seconds exposure (Blustin et al. 2005). Sharapov et al. (2005) found a limiting $I$-band magnitude of $\sim 21$ at 10.52 hours after the burst, while Bikmaev et al. (2005) reported an $R$-band upper limit of $\sim 23$ at 12.75 hours after the event.

Spectroscopy of galaxies close to and inside the XRT error circle revealed a mean redshift of $z = 0.72$ (Berger 2005b; Foley, Bloom & Chen 2005; Prochaska et al. 2006), indicating the possibility that this may also be the redshift of the GRB. This was later refuted by Berger (2006), who argued that the host is a background galaxy at a (photometric) redshift of about 1.8, possibly related to a background cluster of galaxies. This would make GRB 050813 the second most distant (after GRB 060121, de Ugarte Postigo et al. 2006; Levan et al. 2006) short burst for which a redshift could be estimated.

Here we report on a deep follow-up observing campaign of GRB 050813 with telescopes at Paranal, Chile, as well as at Calar Alto and at the Observatorio Sierra Nevada (OSN), Spain. The constraints we can set on any SN component following this burst as well as the faintness of its optical afterglow match well into what is known so far about the properties of short bursts. Throughout this paper we adopt a world model with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.73$ (Spergel et al. 2003), which for $z=0.72$ yields a distance modulus of 43.22 mag. The luminosity distance is $1.36 \times 10^{28}$ cm and 1 arcsec corresponds to 7.23 kpc. If $z=1.8$, the corresponding numbers are 45.7 mag, $4.26 \times 10^{28}$ cm, and 8.55 kpc.
2. Observations and data reduction

A first imaging of the GRB error box was performed with the 1.5-m OSN telescope at Observatorio Sierra Nevada and the Calar Alto 2.2-m telescope equipped with CAFOS starting already 0.5 days after the burst (Gorosabel et al. 2005). Unfortunately, these observations resulted only in upper limits for the magnitude of any optical transient (Table I). In order to set constraints on a rising SN component, we have then carried out deep follow-up observations using VLT/FORS2 in standard resolution (SR) imaging mode with a scale of 0.25 arcsec per pixel (field of view 6′.8 × 6′.8). Observations were performed in the Bessel I band in order to minimize the potential influence of host extinction on the discovery of a fading (afterglow) or a rising (supernova) source. A first run was performed on August 19.061 to 19.088 UT, 5.8 days after the burst. Ten frames were obtained, 200 seconds exposure time each. Seeing conditions were very good, ~ 0.5 arcsec. A second run using the same instrumental setup was performed on August 24.990 to 25.017 UT, 11.7 days after the burst. Atmospheric seeing conditions were even better than during the first observing run, approaching 0.35 arcsec. Both nights were photometric.

The FORS2 images were bias-subtracted and flat-fielded with standard reduction procedures provided within IRAF. Frames obtained on the same night and in the same band were summed together in order to increase the signal-to-noise ratio. Photometry was performed with standard Point Spread Function (PSF) fitting using the DAOPHOT II image data analysis package "PSF-fitting algorithm" (Stetson 1987) within the MIDAS platform. In addition, we performed aperture photometry using the IRAF Aperture Photometry Package Apphot.

Additional spectroscopic observations covering the entire original r = 10 arcsec XRT error circle (Morris et al. 2005) were performed with the Integral Field Unit VIMOS/IFU at the ESO-VLT starting 20 hours after the burst. Unfortunately, these observations could not be implemented into this study due to technical problems with the data.

Figure 1 shows the Swift XRT 90% containment radius reported by Morris et al. (2005) (large circle), the refined error circle by Moretti et al. (2006) (small circle) and, as a small ellipse, the re-analyzed X-ray error box (68% containment radius) given by Prochaska et al.

---

2http://iraf.noao.edu

3The PSF-fitting photometry is accomplished by modeling a two-dimensional Gaussian profile with two free parameters (the half width at half maxima along x and y coordinates of each frame) on at least five unsaturated bright stars in each image.

4http://www.eso.org/projects/esomidas
In the original \( r=10 \) arcsec XRT error circle we identify 11 sources, designated by the letters C, D, E, F and the numbers from 1 to 7. Note that B = X, C = B, 4 = B* and E = C in the nomenclature of Prochaska et al. (2006). The X-ray error box published by Prochaska et al. (2006) contains only two sources, of which #6 is the one identified by Berger (2006) as the possible host galaxy possibly related to a cluster of galaxies at \( z=1.8 \). Nothing can be said at this stage about the redshift of source #7, however. Here, we assume that it is a member of the cluster of galaxies at \( z=0.72 \) (Berger 2005b; Foley, Bloom & Chen 2005; Prochaska et al. 2006).

3. Results

Our two FORS2 observing runs were arranged such that they would allow us to search for a fading (afterglow) as well as for a rising (supernova) component following GRB 050813, supposing \( z=0.72 \). Initially we searched for a transient isolated point source in the original 10 arcsec XRT error circle, but we did not find one. The fact that the sources #2, #5 and #6 (Fig. 1; Table 3) are not detected in the combined image of the first VLT/FORS2 observing run might be due to the presence of the Moon, causing an enhanced sky background level. During the second FORS2 run the sky background was much lower and the seeing even better than during the first observing run. We conclude that any well-isolated afterglow or supernova in this field was fainter than the magnitude limits at the time of the two FORS2 observing runs, \( I=25.1 \) and 25.5, respectively.

3.1. Search for a fading afterglow component

Based on our deep FORS2 observing runs, we searched for a potential fading afterglow superimposed on the brightest extended sources (galaxies) in the field (Table 2). No evidence for variability due to an underlying transient source was found. Prochaska et al. (2006) identified object C and E as elliptical galaxies (Fig. 1), with C being the most likely host candidate based on its location relative to their revised elliptical error circle. In our images source E appears to have an irregular halo which does not support its classification as an elliptical. Image subtraction did not reveal any transient source superimposed on this galaxy.

In order to obtain an upper limit on a possible detection of an afterglow (or a SN) in

\footnote{E. Berger, talk given at “Swift and GRBs: Unveiling the Relativistic Universe”, San Servolo, Venice (Italy), 2006 June 5-9}
the first (second) epoch FORS2 image superimposed source E, we artificially added point
sources of different magnitudes to E and then performed an aperture photometry. These
point sources were selected from the second epoch image. All pixels of the second epoch
image were then set to zero except the pixels of the selected point source of known magnitude
and the resulting image was then shifted and added to the first epoch image. This analysis
showed that we would have been able to detect (at 3 \( \sigma \)) a fading afterglow superimposed on
this galaxy if its \( I \)-band magnitude had been 23.5 at the time of the first FORS2 observation.

3.2. Upper limits on a rising supernova component

One of the main observational characteristics of a short burst should be the absence of a
SN component in the late-time afterglow (Hjorth et al. 2005a), as the merger is not expected
to result in the kind of radioactivity-powered optical display typical for thermonuclear (Type
Ia) and core-collapse (Types II and Ib/c) supernovae. However, mergers may have sub-
relativistic explosions with low amount of ejected mass (Li & Paczyński 1998; Kulkarni 2005),
but they should have a small luminosity. In agreement with these expectations, strong upper
limits could be set so far on any potential SN component accompanying short bursts (cf.
Hjorth et al. 2005a; Fox et al. 2005).

The constraints we can place on a rising SN component for GRB 050813 are less
severe, given the potentially relatively high redshift of this burst. For the cosmological
parameters employed here, SN 1998bw (Galama et al. 1998) redshifted to \( z = 0.72 \) would
have magnitudes of \( I = 24.7 \) and \( I = 23.9 \) during our first and second VLT/FORS observing
run, respectively, after taking into account a Galactic reddening of \( E(B-V) = 0.056 \) mag
(Schlegel, Finkbeiner & Davis 1998) in the direction of GRB 050813. At that brightness level
we would have detected the SN if not superimposed on a much brighter host or strongly ex-
tinguished by dust. More precisely, we conclude that at the time of our second FORS2
observation any supernova following GRB 050813 was at least about 1.5 mag less luminous
than SN 1998bw. While constraints placed on any SN component underlying the afterglow
of e.g. GRB 050509B (Hjorth et al. 2005a) and GRB 050709 (Fox et al. 2005; Covino et al.
2006) are much stronger, this makes a potential SN component following GRB 050813 al-
ready fainter than any of the 11 GRB-SNe of long bursts known to date (Ferrero et al. 2006,
their Figure 6).

On the other hand, we would have been able to detect (at 3 \( \sigma \)) a rising SN component su-
perimposed on the bright galaxy E (Fig. 1) only if its \( I \)-band magnitude had been 23.5 at the
time of the second FORS2 observation. In other words, a SN 1998bw-like component would
be missed in this case. The same holds for a typical type Ia supernova (Krisciunas et al.
which would have had $I=26.9$ and $I=25.4$ at the time of our first and second FORS2 observing run, respectively.

4. Discussion

Short bursts, by phenomenological classification introduced by Kouveliotou et al. (1993), are bursts whose $T_{90}$ duration measured with BATSE was less than 2 sec. Even though it has already been known in the 1990s that $T_{90}$ is a function of energy (and of detector properties), this definition, because of its simplicity, has been widely used even in the HETE-2 and in the Swift era. In principle, having now much more observational data at hand for individual bursts than in the BATSE era, this phenomenological definition/classification scheme calls for a more accurate, namely physical classification scheme.

It is clear that the classification of individual bursts with respect to the nature of their progenitor is difficult. Recent investigations tackle this problem and have led to the suggestion of much more then just one criterium in order to classify a GRB (Donaghy et al. 2006; Norris & Bonnell 2006). As long as no consensus has been reached in the literature what the ultimate criteria are for a burst to be classified as being due to a merger event, in several cases only arguments can be provided that favor one scenario for the other (merger vs. collapse). The detection or non-detection of a SN signal plays a key role in this approach but has come into question recently (see Gehrels et al. 2006; Fynbo et al. 2006; Della Valle et al. 2006; Gal-Yam et al. 2006; Zhang 2006). This leaves the nature of the host galaxy as the strongest argument to detect a GRB due to a merger event, namely if the host is an elliptical galaxy. But the potentially broad range in merger times and hence distances of the merger events from their host galaxies (cf. Belczynski et al. 2006) might also call into question the application of this criterium. GRB 050813 belongs to those bursts that demonstrate all these problems in detail.

One of the main goals of our observing runs was the localization of the afterglow and hence the identification of the GRB host galaxy. Basically, the host cannot be identified with certainty and we have to consider other arguments that favor or disfavor any galaxy visible on the deep FORS2 $I$-band images of the XRT error circle as the potential host. GRB 050813 then joins the increasing list of short bursts with no detected optical afterglow, starting with GRB 050509B (Bloom et al. 2006; Castro-Tirado et al. 2005; Gehrels et al. 2005; Hjorth et al. 2005b). Using the upper limits on the afterglow of GRB 050813 (Table 1) we can follow Kann, Klose & Zeh (2006) and place the properties of this afterglow in the context of other known GRB afterglows (Fig. 2). The long burst afterglows shown in Fig. 2 by solid lines are those from the “Golden Sample” of Kann, Klose & Zeh (2006), i.e.,
those that have sufficient $I$-band data. In addition, we analyzed the available afterglow data on the short bursts GRB 050709 (Hjorth et al. 2005b; Fox et al. 2005; Covino et al. 2006), GRB 050724 (Berger et al. 2005a; Malesani et al. 2007), GRB 051221A (Soderberg et al. 2006) and GRB 060121 (Levan et al. 2006; de Ugarte Postigo et al. 2006) in an analogous way and also included them in Fig. 2 (see the Appendix B for details). As can be seen, short burst optical afterglows are intrinsically very faint, with the afterglows of GRB 050724 and GRB 051221A being about 3 magnitudes fainter than any long burst afterglow in the sample, and GRB 050709 being 4 magnitudes fainter at one day after the burst and assuming $z = 0.72$ (in agreement with the predictions for short burst afterglows; Panaitescu, Kumar & Narayan 2001). They are also significantly fainter than intrinsically faint afterglows of some long GRBs, such as GRB 021211. Only the afterglow of GRB 060121 is comparable with the typical afterglows of long GRBs. The upper limits on the optical afterglow of GRB 050813 show that its luminosity was also far below typical luminosities of (extinction-corrected) afterglows of long bursts. On the other hand, it matches the luminosity region occupied so far by afterglows of the short bursts (with GRB 060121 being the only exception).

Figure 1 shows that there are only two sources in the XRT error ellipse (Prochaska et al. 2006), while there are at least three additional sources in the refined error circle (Moretti et al. 2006). The former might favor a burst related to the very faint sources #6 and #7 (source #6 appears point-like in our images) but it does not even exclude an event in the outer halo of source C, an elliptical galaxy at a redshift of 0.719 (Prochaska et al. 2006). The minimum distance between the border of the error ellipse and the center of this galaxy is 3.2 arcsec, corresponding to a projected distance of 23 kpc. This is less than the projected distance of the error circle of GRB 050509B from the center of its suspected host, an elliptical galaxy at a redshift of $z = 0.225$ (Gehrels et al. 2005). In addition, the minimum angular distance between source E and the border of the error ellipse is 7.1 arcsec, corresponding to a projected distance of 51 kpc. Even this is within the range predicted by recent models of merging compact objects (see Belczynski, Bulik & Kalogera 2002; Perna & Belczynski 2002). The error circle determined by Moretti et al. (2006) is much larger, and thus allows not only source C but also galaxy E at $z = 0.73 \pm 0.01$ (Prochaska et al. 2006) to be the potential host of GRB 050813. This galaxy was classified by Prochaska et al. (2006) as an elliptical galaxy, while our images show morphology that point either to a spiral or to an irregular galaxy. The nature of the fifth, point-like source in the refined error circle, #4, remains undetermined.

While this paper was submitted, a new revised XRT error circle was reported by Butler (2007). This revised error circle is 3.8 arcsec in radius and centered close to a faint edge-on galaxy. This galaxy (source #7, see Fig. 1) was only marginally detected during the first FORS observations. A comparison with the second FORS observations six days later does not provide convincing evidence for a photometric variability due to an underlying point
source.

To summarize, our optical data do not reveal either an afterglow nor a SN component. If GRB 050813 was occurring in a cluster of galaxies at a redshift of \( z = 0.72 \), as it might be indicated by the surrounding galaxy population, then its projected distance from its potential host galaxy could have been of the order of less than 4 to some dozen kpc, depending on the chosen potential host galaxy. The non-detection of the afterglow is well in accord with the faintness of optical afterglows following short bursts (Fig. 2). On the other hand, if the burster would have been at \( z = 1.8 \) (Berger 2006), no SN 1998bw-like component would have been detectable in our images and any afterglow component would have been correspondingly fainter than in the former case (Fig. 3). But even in this case the upper limits we can set on any optical afterglow are consistent with the hypothesis that GRB 050813 was a typical member of the short bursts.

5. Acknowledgements

We thank the staff at ESO/Paranal, in particular C. Dumas, P. D. Lynam, P. Gandhi, N. Huélamo, and E. Jehin, for performing the observations and additional efforts related to that. We thank CAHA and OSN staff for excellent support during some of the observations presented here. P.F., D.A.K., and S.K. acknowledge financial support by DFG grant Kl 766/13-2 and by the German Academic Exchange Service (DAAD) under grant No. D/05/54048. The research activity of J. Gorosabel is supported by the Spanish Ministry of Science through projects AYA2004-01515 and ESP2005-07714-C03-03. We thank the second referee for a rapid reply and a constructive report.

A. The light curves of the short burst afterglows

In Fig. 2 we included those four GRBs that have both an optical afterglow and a redshift derived either from host galaxy spectroscopy or photometry (GRB 060121; de Ugarte Postigo et al. 2006) up to October 2006.

We take data from the following works: GRB 050709: Hjorth et al. (2005b); Fox et al. (2005); Covino et al. (2006). GRB 050724: Berger et al. (2005a); Malesani et al. (2007). GRB 051221A: Soderberg et al. (2006). GRB 060121: Levan et al. (2006); de Ugarte Postigo et al. (2006).

For GRB 050709, we derive a decay slope of \( \alpha = 1.68 \pm 0.15 \) from the \( R_C \)-band light curve. Fox et al. (2005) noted that the late Hubble Space Telescope (HST) data indicate a
steepening of the light curve decay, possibly due to a jet break. Using the \( R_C \)-band decay index, we find a rebrightening (significant at the 5 \( \sigma \) level) in the HST data, but only marginal evidence that the afterglow is fainter than expected from the early decay in the last HST detection. This result is in accordance with Watson et al. (2006). The light curve shown in Fig. 2 is composed of the \( R_C \) data shifted to the HST F814W zero point, plus the HST data. From the \( V, R_C, F8, K' \) spectral energy distribution (SED), we derive a steep uncorrected spectral slope \( \beta_0 = 1.71 \pm 0.17 \). This is indicative of additional source frame extinction. As the host is a blue dwarf galaxy (Fox et al. 2005), we assumed SMC-type dust (Pei 1992). A free fit implies \( \beta = 0.26 \pm 1.16 \) and a host extinction of \( A_V(\text{host}) = 1.46 \pm 1.07 \) mag, a very high value indeed. As the single \( K' \)-data point has a very large error (0.7 mag), this value may not be trustworthy. For a progenitor that has traveled far from its birthplace, an unstratified surrounding medium is expected (density \( \rho \propto r^0 \)). We fixed \( \beta \) to the value derived from the pre-break decay slope \( \alpha_1 \), and find \( \beta = 1.12 \) and \( A_V(\text{host}) = 0.67 \pm 0.19 \) mag. We used these parameters to correct and shift the light curve.

For GRB 050724, the Galactic extinction is high and not well determined. We follow Malesani et al. (2007), who argue, based on the X-ray to optical SED, for \( E_{B-V} = 0.49 \). After correcting for this extinction, we find \( \beta = 0.76 \pm 0.07 \) and no evidence for source frame extinction, in accordance with Malesani et al. (2007). The light curve is mostly \( I_C \) data anyway, we add \( V, R_C \) and \( K \) data shifted to the \( I_C \) zero point.

In the case of GRB 051221A, we find that the light curve decays as a single power-law with a slope \( \alpha = 0.94 \pm 0.03 \), in accordance with Soderberg et al. (2006). We derive a flat spectral slope \( (\beta = -0.16 \pm 0.84) \) from the \( r'i'z' \) spectral energy distribution, but caution that the errors of the \( i' \) and \( z' \) data are very large. Assuming an unstratified surrounding medium and a cooling frequency blueward of the optical bands, we derive \( \beta = 0.62 \) (coupled with a typical power-law index of the electron distribution function of \( p = 2.25 \); cf. Kann, Klose & Zeh 2006). We used this spectral slope and assume no additional extinction to shift the light curve.

Combining the data from Levan et al. (2006) and de Ugarte Postigo et al. (2006) of GRB 060121, we find that the zero points of the two data sets differ. We shifted the data from de Ugarte Postigo et al. (2006) to the fainter zero point of Levan et al. (2006). The light curve has a complex shape and seems to include several rebrightenings (Fig. 2). It is composed of \( I_C \) data and \( R_C \) data shifted to the \( I_C \) zero point. We used the redshift and host galaxy extinction derived by de Ugarte Postigo et al. (2006), assuming the more probable redshift of \( z = 4.6 \), and a spectral slope in the optical of \( \beta = 0.6 \), as derived by the authors cited above.

In all cases, except for GRB 060121, the afterglow data do not contain any host contri-
bution. For GRB 060121, we used a host galaxy magnitude derived from the HST measurements (Levan et al. 2006). To correct for Galactic extinction, we used the value derived from the maps of Schlegel, Finkbeiner & Davis (1998) for GRB 050709, 051221A and 060121, and $E_{B-V} = 0.49$ mag for GRB 050724 (as suggested by Malesani et al. 2007).

REFERENCES

Aloy, M. A., Janka, H.-T., & Müller, E. 2005, A&A, 436, 273
Balázs, L. G., Mészáros, A., & Horváth, I. 1998, A&A, 339, 1
Belczynski, K., Bulik, T., & Kalogera, V. 2002, ApJ, 571, L147
Belczynski, K., et al. 2006, ApJ, 648, 1110
Berger, E., et al. 2005, Nature, 438, 988
Berger, E. 2005, GCN 3801
Berger, E. 2006, in: Proc. Gamma-Ray Bursts in the Swift era, eds. S. S. Holt, N. Gehrels, J. A. Nousek, AIP Conf. Proc. 836, 33
Bikmaev, I., et al. 2005, GCN 3797
Bloom, J. S., et al. 2007, ApJ, 654, 878
Bloom, J. S., et al. 2006, ApJ, 638, 354
Bloom, J. S., Dupree, A., Chen, H-W., & Prochaska, J. X. 2005, GCN 3672
Blustin, A. J., et al. 2005, GCN 3791
Butler, N. R. 2007, AJ, 133, 1027
Castro-Tirado, A. J., et al. 2005, A&A, 439, L15
Covino, S., et al. 2006, A&A, 447, L5
Della Valle, M., et al. 2006, Nature, 444, 1050
de Ugarte Postigo, A., et al. 2006, ApJ, 648, L83
Donaghy, T. Q., et al. 2006, ApJ, submitted (astro-ph/0605570)
Faber, J. A., Baumgarte, T. W., Shapiro, S. L., & Taniguchi, K. 2006, ApJ, 641, L93
Ferrero, P., et al. 2006, A&A, 457, 857
Foley, R. J., Bloom, J. S., & Chen, H.-W. 2005, GCN 3808
Fox, D. B., et al. 2005, Nature, 437, 845
Frederiks, D. D., et al. 2006, Astronomy Letters, 33, 19
Fryer, C. L., Woosley, S. E., & Hartmann, D. H. 1999, ApJ, 526, 152
Fynbo, J. P. U., et al. 2006, Nature, 444, 1047
Galama, T. J., et al. 1998, Nature, 395, 670
Gal-Yam, A., et al. 2006, Nature, 444, 1053
Gehrels, N., et al. 2005, Nature, 437, 851
Gehrels, N., et al. 2006, Nature, 444, 1044
Gladders, M., Berger, E., Morell, N., & Roth, M. 2005, GCN 3798
Golenetskii, S. et al. 2005, GCN 4197
Gorosabel, J., et al. 2005, GCN 3796
Gorosabel, J., et al. 2006, A&A, 450, 87
Hjorth, J., et al. 2003, Nature, 423, 847
Hjorth, J., et al. 2005a, ApJ, 630, L117
Hjorth, J., et al. 2005b, Nature, 437, 859
Kann, D. A., Klose, S., & Zeh, A. 2006, ApJ, 641, 993
Kouveliotou, C., et al. 1993, ApJ, 413, L101
Krisciunas, K., et al. 2003, AJ, 125, 166
Kulkarni, S. R. 2005, astro-ph/0510256
La Parola, V., et al. 2006, A&A, 454, 753
Lee, W. H., Ramirez-Ruiz, E., & Granot, J. 2005, ApJ, 630, L165
Levan, A. J., et al. 2006, ApJ, 648, L9
Li, L. X., & Paczyński, B. 1998, ApJ, 507, L59
Li, W. 2005, GCN 3794
Malesani, D., et al. 2006, GCN 4561
Malesani, D., et al. 2007, A&A, in press [arXiv:0706.1273]
Moretti, A., et al. 2006, A&A, 448, L9
Morris, D. C., et al. 2005, GCN 3790
Norris, J. P., & Bonnell, J. T. 2006, ApJ, 643, 266
Oechslin, R., & Janka, H.-Th. 2006, MNRAS, 368, 1489
Ofek, E. O., et al. 2006, ApJ, 652, 507
Panaitescu, A., Kumar, P., & Narayan, R. 2001, ApJ, 561, L171
Paczyński, B. 1998, ApJ, 494, L45
Pedersen, K., et al. 2005, ApJ, 634, L17
Pei, Y. C. 1992, ApJ, 395, 130
Perna, R. & Belczynski, K. 2002, ApJ, 570, 252
Pian, E., et al. 2006, Nature, 442, 1011
Prochaska, J. X., et al. 2006, ApJ, 642, 989
Prochaska, J. X., Chen, H-W., Bloom, J. S., & Stephens, A. 2005, GCN 3679
Racusin, J. L., et al. 2006, GCN 5378
Retter, A., et al. 2005, GCN 3788
Roming, P. W. A., et al. 2006, ApJ, 651, 985
Rosswog, S. 2005, ApJ, 634, 1202
Ruffert, M. & Janka, H.-Th. 2001, A&A, 380, 544
Sari, R., Piran, T. & Narayan, R. 1998, ApJ, 497, L17
Sato, G., et al. 2005, GCN 3793
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sharapov, D., Ibrahimov, M., Pozanenko, A., & Rumyantsev, V. 2005, GCN 3857
Soderberg, A. M., & Berger, E. 2005, GCN 4375
Soderberg, A. M., et al. 2006, ApJ, 650, 261
Spergel, D. N., et al. 2003, ApJS, 148, 175
Stanek, K. Z., et al. 2003, ApJ, 591, L17
Stetson, P. B. 1987, PASP, 99, 191
Tanvir, N. R., Chapman, R., Levan, A. J., & Priddey, R. S. 2005, Nature, 438, 991
Watson, D., et al. 2006, A&A, 454, L123
Woosley, S. E., & Bloom, J. S. 2006, Ann. Rev. Astron. Astroph., 44, 507
Zhang, B. 2006, Nature 444, 1010

This preprint was prepared with the AAS \LaTeX{} macros v5.2.
Fig. 1.— VLT $I$-band image of the GRB field obtained 11 days after the burst, showing the original 10 arcsec (radius) XRT error circle of GRB 050813 (Morris et al. 2005) (large circle), the refined error circle by Moretti et al. (2006) (small circle, center around source #4), the revised error ellipse (Prochaska et al. 2006), the refined error circle by Butler (2007) (small circle, center around source #7) and the objects listed in Tables 2 and 3.
Fig. 2.— The $I$-band light curves of all afterglows from the “Golden Sample” of Kann, Klose & Zeh (2006) after correction for Galactic and for host extinction and after shifting them to a common redshift of $z=0.72$, the potential redshift of GRB 050813. Two long GRB supernova rebrightenings are indicated. Also shown are the $I$-band afterglows of the short bursts GRB 050709, 050724, 051221A and 060121 shifted in a similar way, and our upper limits on any afterglow or supernova from GRB 050813 (upside-down triangles). For GRB 060121 a redshift of $z = 4.6$ (de Ugarte Postigo et al. 2006) is assumed here.
Fig. 3.— The same as Fig. 2 but for a redshift of 1.8
Table 1. Observing log of the GRB 050813 field

| Date (days) | $t - t_0^a$ [days] | Mag\textsuperscript{b} | Exposure [s] | Filter | Telescope       |
|------------|---------------------|-------------------------|--------------|--------|-----------------|
| 13.8333    | 0.5519              | 22.8                    | 10×600       | I      | 1.5m OSN        |
| 13.8708    | 0.5894              | 23.3                    | 23×180       | R      | 2.2m, CAFOS     |
| 14.8475    | 1.5661              | 23.1                    | 24×300       | R      | 2.2m, CAFOS     |
| 19.0606    | 5.7792              | 25.1                    | 10×200       | I      | 8.2m, FORS2     |
| 24.9901    | 11.7087             | 25.5                    | 10×200       | I      | 8.2m, FORS2     |

\textsuperscript{a}$t_0 = 2005$ August 13.2814, the time of the burst. All dates refer to August 2005 and give the time of the start of the first exposure.

\textsuperscript{b}The limiting magnitude of the combined image.
Table 2. The objects used for the calibration of the photometry (A,B,F,G,H,I) and the brightest galaxies in the XRT error circle (C,D,E).

| #<sup>a</sup> | RA<sup>b</sup>   | DEC<sup>b</sup> | $I$         |
|---------|----------------|----------------|------------|
| A       | 16:07:57.72    | +11:15:02.24   | 24.68 ± 0.35|
| B       | 16:07:57.50    | +11:15:02.13   | 21.83 ± 0.09|
| C       | 16:07:57.19    | +11:14:53.15   | 22.43 ± 0.12|
| D       | 16:07:57.16    | +11:14:46.86   | 23.38 ± 0.22|
| E       | 16:07:57.01    | +11:14:47.61   | 22.74 ± 0.28|
| F       | 16:07:56.85    | +11:15:01.80   | 20.88 ± 0.03|
| G       | 16:07:56.66    | +11:15:02.87   | 23.61 ± 0.19|
| H       | 16:07:56.53    | +11:15:01.11   | 22.85 ± 0.14|
| I       | 16:07:56.10    | +11:14:47.34   | 23.50 ± 0.17|

<sup>a</sup>The numbering follows Fig. 1.

<sup>b</sup>Epoch J2000
Table 3. The photometry of the fainter sources in the XRT error circle.

| #  | RA       | DEC      | $I_{\text{run 1}}$ | $I_{\text{run 2}}$ |
|----|----------|----------|---------------------|---------------------|
| 1  | 16:07:57.00 | +11:14:43.83 | 24.7 < $I$ < 24.9 | 24.4 < $I$ < 25.4 |
| 2  | 16:07:56.85 | +11:14:42.91 | > 25.1             | 24.4 < $I$ < 25.5 |
| 3  | 16:07:56.66 | +11:14:43.58 | 24.69 ± 0.24       | 24.44 ± 0.10       |
| 4  | 16:07:57.07 | +11:14:53.65 | 24.63 ± 0.30       | 24.67 ± 0.13       |
| 5  | 16:07:56.40 | +11:14:48.35 | > 25.1             | 25.47 ± 0.25       |
| 6  | 16:07:56.91 | +11:14:55.91 | > 25.1             | 25.64 ± 0.28       |
| 7  | 16:07:57.07 | +11:14:57.43 | 24.7 < $I$ < 25.1 | 25.41 ± 0.25       |

a The numbering follows Fig. 1.

b Epoch J2000

c Run 1 and run 2 refer to the first and second VLT/FORS observations, respectively.