2012

The late-time afterglow of the extremely energetic short burst GRB 090510 revisited

A. Nicuesa Guelbenzu

S. Klose

T. Krühler

J. Greiner

A. Rossi

See next page for additional authors

Recommended Citation

Guelbenzu, N. .... A. Updike, et al. 2012. "The Late-Time Afterglow of the Extremely Energetic Short Burst GRB 090510 Revisited." *Astronomy & Astrophysics* 538: 7.

Authors
A. Nicuesa Guelbenzu, S. Klose, T. Krühler, J. Greiner, A. Rossi, D.A. Kann, F. Olivares, A. Rau, P.M.J. Afonso, J. Elliott, R. Filgas, A. Küpcü Yoldas, S. McBreen, M. Nardini, P. Schady, S. Schmidl, V. Sudilovsky, Adria Updike, and A. Yoldas

A&A 538, L7 (2012)
DOI: 10.1051/0004-6361/201118416

Astronomy & Astrophysics

Letter to the Editor

The late-time afterglow of the extremely energetic short burst GRB 090510 revisited*

A. Nicuesa Guelbenzu[1], S. Klose[1], T. Krühler[2,3,4], J. Greiner[2], A. Rossi[1], D. A. Kann[1], F. Olivares[2], A. Rau[2], P. M. J. Afonso[2,5], J. Elliott[2], R. Filgas[2], A. Küpcü Yoldaş[6], S. McBreen[7], M. Nardini[2], P. Schady[2], S. Schmidl[1], V. Sudilovsky[2], A. C. Updike[8,9,10], and A. Yoldaş[6]

1 Thüringer Landessternwarte Tautenburg, Sternwarte 5, 07778 Tautenburg, Germany
e-mail: ana@tls-tautenburg.de
2 Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstraße, 85748 Garching, Germany
3 Universe Cluster, Technische Universität München, Boltzmannstraße 2, 85748 Garching, Germany
4 Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen, Denmark
5 American River College, Department of Physics and Astronomy, 4700 College Oak Drive, Sacramento, CA 95841, USA
6 Institute of Astronomy, University of Cambridge, Madingley Road CB3 0HA, Cambridge, UK
7 School of Physics, University College Dublin, Dublin 4, Republic of Ireland
8 Clemson University, Department of Physics and Astronomy, Clemson, SC 29634-0978, USA
9 CRESST and the Observational Cosmology Laboratory, NASA/GSFC, Greenbelt, MD 20771, USA
10 Department of Astronomy, University of Maryland, College Park, MD 20742, USA

Received 7 November 2011 / Accepted 24 December 2011

ABSTRACT

Context. The *Swift* discovery of the short burst GRB 090510 has raised considerable attention mainly because of two reasons: first, it had a bright optical afterglow, and second it is among the most energetic events detected so far within the entire GRB population (long plus short). The afterglow of GRB 090510 was observed with *Swift*/UVOT and *Swift*/XRT and evidence of a jet break around 1.5 ks after the burst has been reported in the literature, implying that after this break the optical and X-ray light curve should fade with the same decay slope.

Aims. As noted by several authors, the post-break decay slope seen in the UVOT data is much shallower than the steep decay in the X-ray band, pointing to a (theoretically hard to understand) excess of optical flux at late times. We assess here the validity of this peculiar behavior.

Methods. We reduced and analyzed new afterglow light-curve data obtained with the multichannel imager GROND. These additional $g'r'i'z'$ data were then combined with the UVOT and XRT data to study the behavior of the afterglow at late times more stringently.

Results. Based on the densely sampled data set obtained with GROND, we find that the optical afterglow of GRB 090510 did indeed enter a steep decay phase starting around 22 ks after the burst. During this time the GROND optical light curve is achromatic, and its slope is identical to the slope of the X-ray data. In combination with the UVOT data this implies that a second break must have occurred in the optical light curve around 22 ks post burst, which, however, has no obvious counterpart in the X-ray band, contradicting the interpretation that this could be another jet break.

Conclusions. The GROND data provide the missing piece of evidence that the optical afterglow of GRB 090510 did follow a post-jet break evolution at late times. The break seen in the optical light curve around 22 ks in combination with its missing counterpart in the X-ray band could be due to the passage of the injection frequency across the optical bands, as already theoretically proposed in the literature. This is possibly the first time that this passage has been clearly seen in an optical afterglow. In addition, our results imply that there is no more evidence for an excess of flux in the optical bands at late times.

Key words. gamma-ray burst: individual: GRB 090510

1. Introduction

After the first GRB was discovered in 1967 (Klebesadel et al. 1973), GRB research has evolved rapidly. In the early 1990s it became clear that GRBs come in two flavors, long and short, with the borderline around 2 s (Kouveliotou et al. 1993). Thanks to three generations of high-energy satellites, BeppoSAX (Piro et al. 1998), HETE-2 (Ricker 2002), and *Swift* (Gehrels et al. 2004), it is now known that long GRBs are linked to the core collapse of massive stars (Woosley & Bloom 2006), while short bursts are most likely linked to compact stellar mergers in all morphological types of galaxies (Nakar 2007; Fong et al. 2010). Short bursts are much less frequently observed than long GRBs so that our knowledge about short burst progenitors is much less complete.

Since mid-2007 our group operates the seven-band imager GROND mounted at the 2.2 m ESO/MPG telescope on La Silla, especially designed for GRB follow-up observations (Greiner et al. 2008). Every observable burst is followed with delay times down to 2.5 min between the GRB trigger and the first exposure.

GRB 090510 triggered *Swift*/BAT (Hoversten et al. 2009a) and *Fermi*/GBM (Guiriec et al. 2009) on 10 May 2009 at 00:23:00 UT, as well as *Fermi*/LAT at 00:23:01 UT (Ohno & Pelassa 2009). In the *Swift*/BAT energy window it had a duration

* Appendix A is available in electronic form at http://www.aanda.org

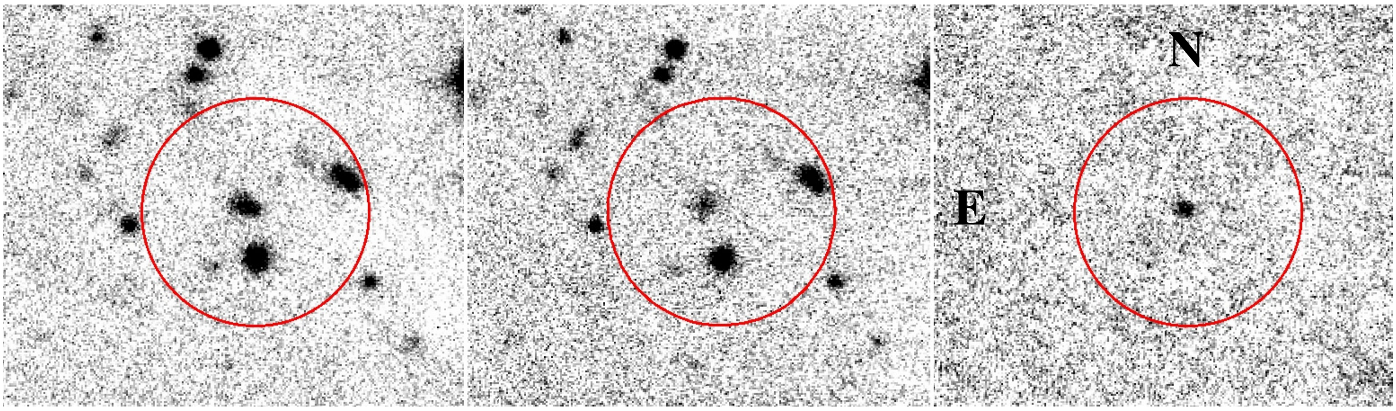

Fig. 1. GROND ($g'r'i'z'$) white band finding chart of the afterglow of GRB 090510. *Left*: the afterglow plus its host galaxy on the night of the burst between 22 ks and 36 ks after the trigger. The afterglow flux dominates the western part of its host galaxy. (North is up and east is to the left.) *Middle*: in the second night the afterglow faded away, with only the host galaxy visible. *Right*: image subtraction between the first and the second epoch white band image clearly revealing the afterglow. The circle with a radius of 10″, centered on the position of the afterglow, is just drawn to guide the eye.

of T_{90} [15, 350 keV] = 0.3 ± 0.1 s (Hoversten et al. 2009b). *Swift*/XRT started observing the field about 94 s after the trigger and the X-ray afterglow was immediately found (Hoversten et al. 2009a). *Swift*/UVOT began observations shortly after the XRT, and an optical afterglow candidate was also seen (Marshall & Hoversten 2009; Kuin & Hoversten 2009), which was soon confirmed by the Nordic Optical Telescope (Olofsson et al. 2009) and by GROND (Olivares et al. 2009). The redshift of its underlying host galaxy was finally measured using VLT/FORS2 about 2.3 days after the trigger ($z = 0.903$; Rau et al. 2009; McBreen et al. 2010).

GRB 090510 is not only one of the few short bursts with a clear afterglow detection in the optical bands, but it is also especially unique because it is among the most energetic events detected so far in the entire GRB population (long plus short). In particular, a 31 GeV photon from this burst (Abdo et al. 2009) is the second highest energy photon ever received from a GRB (see Fig. 5 in Piron & Connaughton 2011). Naturally, the afterglow of GRB 090510 was of special interest, too. Remarkably, all studies of its afterglow (see Sect. 3.3) agree on one point: when compared to its X-ray light curve, its computed late-time decay slope in the UVOT white band is difficult to understand within the framework of the standard afterglow model.

Here we present additional photometry of the optical afterglow of GRB 090510 obtained with GROND from about 22 ks to 36 ks after the burst, leading to a re-evaluation of its late-time evolution.

2. Observations and data reduction

GROND started observing the field 6.2 h after the burst and continued for 3.5 h. Owing to visibility constraints from ESO/La Silla, GROND could not be on target earlier. The following night, the field was observed again with GROND for 1.5 h. Data was reduced in a standard fashion via standard PSF photometry using DAOPHOT and ALLSTAR tasks under IRAF (Tody 1993), similar to the procedure described in Krühler et al. (2008) and Yoldaş et al. (2008). Calibrations were performed against the SDSS[1]. Magnitudes were corrected for Galactic extinction, assuming $E(B-V) = 0.02$ mag (Schlegel et al. 1998) and a ratio of total-to-selective extinction of $R_V = 3.1$.

[1] http://www.sdss.org/dr7/

3. Results and discussion

3.1. The afterglow light curve

The first night, the GRB host galaxy is clearly visible in the optical images, with the afterglow light dominating its western part (Fig. 1). While on the first night the afterglow was detected in $g'r'i'z'$ but not in JHK_s, and the second night there was no sign of an afterglow in any band, except the host galaxy. Image subtraction clearly reveals the afterglow between the first- and the second-epoch of the combined $g'r'i'z'$ images using HOTPANTS[2]. Its coordinates measured against the USNO-B1 catalog are RA (J2000) = 22:14:12.53, Dec = −26:34:59.0, with an error of 0.″2 in each coordinate. The afterglow lies about 1.″2 west of the center of its host galaxy (see also McBreen et al. 2010).

During the first night, GROND detected the fading afterglow in all optical bands (Fig. 2, Table A.1). For this timespan, from 22 ks to 36 ks, the r'-band light curve can be fit by a single power law with a slope of $\alpha_{\rm opt} = 2.37 \pm 0.29$ ($\chi^2_{\rm red} = 0.49$; 23 degrees of freedom)[3]. This slope also fits the $g'i'z'$ band data; i.e., the evolution of the optical afterglow was achromatic[4]. Within its 1σ error, it also matches the late-time decay slope of the X-ray afterglow ($\alpha_X = 2.18 \pm 0.10$; De Pasquale et al. 2010). The obtained decay slope is substantially different from what is reported by De Pasquale et al. (2010) based on *Swift*/UVOT data.

3.2. The SED of the afterglow

The X-ray data for $t < 20$ ks lead to a time-averaged spectral slope of $\beta_X = 0.8 \pm 0.1$, while the X-ray data for $t > 20$ ks give $\beta_X = 1.4 \pm 0.7$ (see the *Swift*/XRT repository, Evans et al. 2007). The XRT data are therefore consistent with having a spectral index of $\beta_X = 0.8$ throughout the observations. This suggests that the cooling frequency ν_c lies above the X-ray band in the whole X-ray data set (De Pasquale et al. 2010).

[2] http://www.astro.washington.edu/users/becker/hotpants.html

[3] In the following we use the standard notation for the flux density, $F_\nu(t) \propto t^{-\alpha} \nu^{-\beta}$.

[4] A joint fit leads to the same conclusion but has a slightly higher $\chi^2_{\rm red}$ of 0.59.

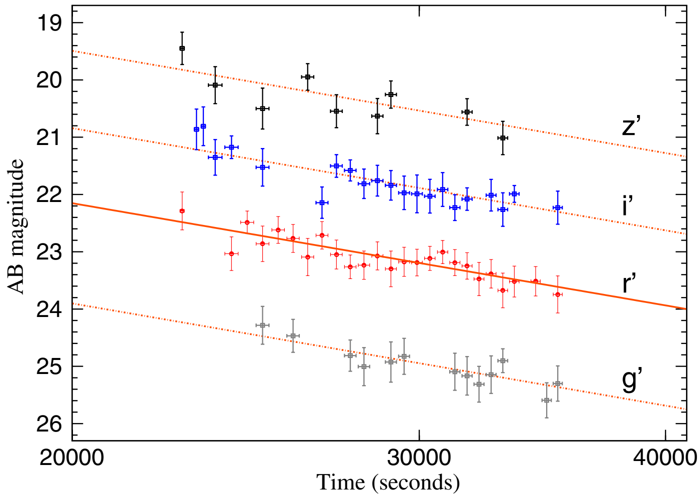

Fig. 2. GROND $g'r'i'z'$-band light curves of the afterglow of GRB 090510 (*from bottom to top*). For reasons of clarity the g', i', z' bands were shifted by $+1.4, -1.0, -2.0$ mag, respectively. The solid straight line is the best fit of the r'-band data, and the broken lines are its corresponding shifts to the other bands. Shown are all data points with a 1σ error of $\lesssim 0.35$ mag (see Table A.1).

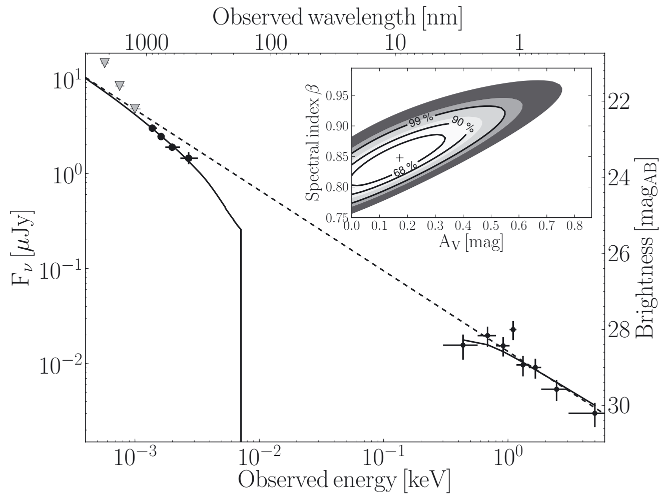

Fig. 3. *Swift*/XRT (Evans et al. 2007) to optical/NIR (GROND) spectral energy distribution of the afterglow of GRB 090510 at $t = 31$ ks after the burst. The inset shows the $\beta_{\rm opt}$ vs. $A_V^{\rm host}$ plane, constraining their corresponding error bars. Filled triangles refer to the GROND-observed NIR upper limits ($J = 22.2$, $H = 21.6$, and $K_s = 21.0$), filled circles to the observed optical magnitudes (g', r', i', z').

Figure 3 shows the best SED fit from the optical to the X-rays using $N_{\rm H}^{\rm Gal} = 1.7 \times 10^{20}$ cm^{-2} (Kalberla et al. 2005). For SMC dust and a redshift of $z = 0.903$, it finds a host galaxy extinction of $A_V^{\rm host} = 0.17^{+0.21}_{-0.17}$ mag, a gas column density of $N_{\rm H}^{\rm host} = 0.05^{+0.15}_{-0.05} \times 10^{22}$ cm^{-2}, and a spectral slope of $\beta_{\rm opt} = 0.85 \pm 0.05$ (χ^2/d.o.f. = 0.93).

3.3. What the second light curve break represents

As pointed out by several authors, the optical light-curve fit based on UVOT data is difficult to understand when compared to the X-ray band. A suggested post-break decay slope of $\alpha_{\rm opt} \sim 1.1$ (De Pasquale et al. 2010) is very shallow when compared to the corresponding X-ray light-curve decay ($\alpha_X = 2.18 \pm 0.10$), implying that the optical bands show an excess of flux at late times (Corsi et al. 2010; De Pasquale et al. 2010; He et al. 2011; Kumar & Barniol Duran 2010; Panaitescu 2011).

At first we note that the steep decay of the optical flux seen by GROND ($\alpha_{\rm opt} = 2.37 \pm 0.29$; Sect. 3.1) cannot be explained as pre-jet break evolution. In our data base of afterglow light curves with a well-observed pre- and post-jet break evolution (Kann et al. 2010, 2011), we do not have a single case where the pre-break decay slope is as steep as that. We conclude that at the time when the optical afterglow was monitored by GROND the jet-break had already occurred, and the evolution of the afterglow was in the post-jet break decay phase, confirming the finding of De Pasquale et al. (2010) based on the X-ray light curve. Second, in the GROND $g'r'i'z'$ light curve data there is no evidence of any break, and the decay is achromatic. The UVOT data then show (De Pasquale et al. 2010, their Fig. 1) that a break must have occurred shortly before GROND started observing.

Using the data published in De Pasquale et al. (2010), we fitted the UVOT white-band magnitudes again. At first we assumed a double-broken power law (for the procedure see Schulze et al. 2011) with fixed break times at $t_{\rm b1} = 1.4$ ks (based on the X-ray data, De Pasquale et al. 2010) and $t_{\rm b2} = 22$ ks. Using a smoothing parameter of $n_1 = n_2 = 10.0$ (see Beuermann et al. 1999) for the first and second breaks, respectively, and a late-time decay slope of $\alpha_3 = 2.4$ (Sect. 3.1), this gives an early-time slope of $\alpha_1 = -0.2 \pm 0.2$ and $\alpha_2 = 0.8 \pm 0.1$ (Fig. 4, blue dashed line). A relatively sharp break at $t_{\rm b2}$ is required (defined by n_2) since the GROND data do not show evidence of any curvature in the light curve (Fig. 2). The UVOT two data points at 18 ks and 100 ks are strong outliers, however[5]. This solution suggests we interpret α_2 as a normal pre-jet break decay slope. There is, however, no clear evidence of a corresponding (i.e., achromatic) break in the X-ray light curve, contradicting this interpretation and in this way not affecting the generally excepted idea of a jet break time already around 1.4 ks after the burst (Corsi et al. 2010; De Pasquale et al. 2010; He et al. 2011; Kumar & Barniol Duran 2010; Panaitescu 2011).

Another approach for fitting the UVOT data is suggested by a model discussed by De Pasquale et al. (2010) and Kumar & Barniol Duran (2010). When interpreting the XRT/UVOT data, these authors point out that the flat UVOT light curve decay for $t \gtrsim 1$ ks ($\alpha_{\rm opt} \sim 1.1$) can be understood if, at the time when UVOT was observing, the injection frequency was (still) above the optical bands ($\nu_{\rm opt} < \nu_m$) and the afterglow was in the post-jet-break phase. While theoretically this suggests a decay slope of $\alpha = 1/3$ (e.g., Zhang & Mészáros 2004), these authors argue that possibly the crossing of ν_m through the UVOT bands affected the measured decay slope, making it flatter. In addition, these authors note that the UVOT light curve does not show evidence of any steepening to a decay slope with $\alpha = p$, where p is the power-law index of the electron distribution function, a steepening that is expected once ν_m has passed through the optical bands. The GROND data now suggest re-evaluating this idea, since the expected steepening to $\alpha = p$ is indeed seen in the data but was originally not clearly evident in the sparse UVOT data set.

When following this model, a possible fit of the UVOT data with a double-broken power law is also shown in Fig. 4 (gray line). It uses fixed $\alpha_1 = -0.2, \alpha_2 = 1/3$, and $\alpha_3 = 2.4$, fixed break times as mentioned before, as well as $n_1 = n_2 = 10$. While this fit underpredicts the UVOT optical flux for $t < 2$ ks by a

[5] In the second night GROND was observing between 116 ks and 122 ks after the burst. We do not see evidence of rebrightening.

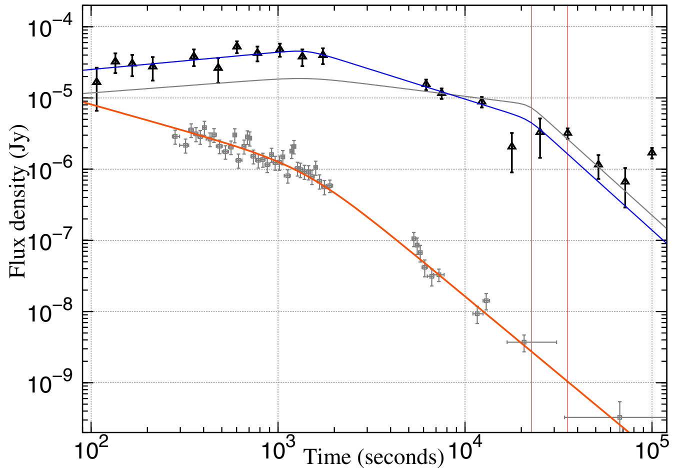

Fig. 4. Best fit of the UVOT *white*-band data (black triangles, taken from De Pasquale et al. 2010, their Fig. 1) for two models that require a second break in the UVOT light curve at 22 ks (see Sect. 3.3). Also shown are the X-ray data, shifted in flux density by a factor of 10^4. The two vertical lines highlight the time interval in which GROND was observing.

factor of ~2, for $t > 2$ ks it reasonable agrees with the observational data. In particular, there is no more evidence of any excess of flux in the UVOT bands at late times (except for the UVOT data point at 100 ks; see footnote #5). Clearly, the underprediction of the optical flux at very early times is a shortcoming of this approach. It remains open whether the very early optical flux could have been affected by rebrightening episodes, similar to what has been seen in, e.g., the afterglow of GRB 080928 (Rossi et al. 2011).

Is the second light curve break definitely caused by the passage of ν_m across the optical bands? At least one shortcoming of this interpretation could be that, if $\nu_m \sim 3$ eV at $t = 20$ ks, then this predicts a relatively high value for the injection frequency at very early times, notably higher than suggested by detailed numerical models of the afterglow (Kumar & Barniol Duran 2010). This issue cannot be solved here. On the other hand, if the second light-curve break were the classical jet break, this would call for a complete re-evaluation of the afterglow parameters, and we would be confronted with the problem of a very sparse X-ray data set around $t = 20$ ks, which would make such an approach even more speculative.

4. Summary and conclusions

We have presented GROND multichannel data of the optical afterglow of GRB 090510 obtained between 22 ks and 36 ks after the burst. These data suggest that, while GROND was observing, the afterglow was in the post-jet break decay phase with a slope of $\alpha \sim 2.4$. In combination with *Swift*/UVOT data, this implies that, in addition to a break at 1.4 ks, a second break occurred in the optical light curve around 22 ks after the burst. The lack of any evidence of a corresponding break in the X-ray light curve at 22 ks disfavors the idea that this is a jet break. Following the discussion in De Pasquale et al. (2010) and Kumar & Barniol Duran (2010), this second break could be understood however as the passage of the injection frequency ν_m across the optical bands, when the afterglow was in the post-jet break decay phase. Furthermore, we find that the GROND data resolve the original issue of a potential excess of flux in the optical bands at late times. The late-time decay slope in the optical bands after 22 ks (i.e., after the passage of ν_m) is, within the errors, identical to the slope of the X-ray light curve, as expected for a post-jet break evolution. We conclude that there is no longer any evidence of an excess of flux in the optical bands at late times. After 22 ks, the evolution of the afterglow was achromatic from the optical to the X-ray band.

Acknowledgements. A.N.G., D.A.K., and S.K. acknowledge support by grant DFG Kl 766/16-1. A.N.G., A.R., D.A.K., and A.U. are grateful for travel funding support through the MPE. T.K. acknowledges funding by the DFG cluster of excellence "Origin and Structure of the Universe", F.O.E. funding of his Ph.D. through the DAAD, M.N. support by DFG grant SA 2001/2-1 and P.S. by DFG grant SA 2001/1-1. Part of the funding for GROND (both hardware and personnel) was generously granted by the Leibniz-Prize to G. Hasinger (DFG grant HA 1850/28-1). This work made use of data supplied by the UK Swift science data center at the University of Leicester. We thank the referee for a rapid reply and a careful reading of the manuscript.

References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, Nature, 462, 331
Beuermann, K., Hessman, F. V., Reinsch, K., et al. 1999, A&A, 352, L26
Corsi, A., Guetta, D., & Piro, L. 2010, ApJ, 720, 1008
De Pasquale, M., Schady, P., Kuin, N. P. M., et al. 2010, ApJ, 709, L146
Evans, P. A., Beardmore, A. P., Page, K. L., et al. 2007, A&A, 469, 379
Fong, W., Berger, E., & Fox, D. B. 2010, ApJ, 708, 9
Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, ApJ, 611, 1005
Greiner, J., Bornemann, W., Clemens, C., et al. 2008, PASP, 120, 405
Guiriec, S., Connaughton, V., & Briggs, M. 2009, GRB Coordinates Network, 9336
He, H.-N., Wu, X.-F., Toma, K., Wang, X.-Y., & Mészáros, P. 2011, ApJ, 733, 22
Hoversten, E. A., Barthelmy, S. D., Burrows, D. N., et al. 2009a, GRB Coordinates Network, 9331
Hoversten, E. A., Krimm, H. A., Grupe, D., et al. 2009b, GCN Report, 218, 1
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775
Kann, D. A., Klose, S., Zhang, B., et al. 2010, ApJ, 720, 1513
Kann, D. A., Klose, S., Zhang, B., et al. 2011, ApJ, 734, 96
Klebesadel, R. W., Strong, I. B., & Olson, R. A. 1973, ApJ, 182, L85
Kouveliotou, C., Meegan, C. A., Fishman, G. J., et al. 1993, ApJ, 413, L101
Krühler, T., Küpcü Yoldaş, A., Greiner, J., et al. 2008, ApJ, 685, 376
Kuin, N. P. M., & Hoversten, E. A. 2009, GRB Coordinates Network, 9342, 1
Kumar, P., & Barniol Duran, R. 2010, MNRAS, 409, 226
Marshall, F. E., & Hoversten, E. A. 2009, GRB Coordinates Network, 9332, 1
McBreen, S., Krühler, T., Rau, A., et al. 2010, A&A, 516, A71
Nakar, E. 2007, Phys. Rep., 442, 166
Ohno, M., & Pelassa, V. 2009, GRB Coordinates Network, 9334
Olivares, F., Klose, S., Kruehler, T., & Greiner, J. 2009, GRB Coordinates Network, 9352, 1
Olofsson, G., Ergon, M., Malesani, D., et al. 2009, GRB Coordinates Network, 9338, 1
Panaitescu, A. 2011, MNRAS, 414, 1379
Piro, L., Heise, J., Jager, R., et al. 1998, A&A, 329, 906
Piron, F., & Connaughton, V. 2011, CR Phys., 12, 267
Rau, A., McBreen, S., & Kruehler, T. 2009, GRB Coordinates Network, 9353, 1
Ricker, G. 2002, in 34th COSPAR Scientific Assembly, 34
Rossi, A., Schulze, S., Klose, S., et al. 2011, A&A, 529, A142
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schulze, S., Klose, S., Björnsson, G., et al. 2011, A&A, 526, A23
Tody, D. 1993, ASP Conf. Ser., 52, 173
Woosley, S. E., & Bloom, J. S. 2006, ARA&A, 44, 507
Yoldaş, A. K., Krühler, T., Greiner, J., et al. 2008, AIP Conf. Ser., 1000, 227
Zhang, B., & Mészáros, P. 2004, Int. J. Mod. Phys. A, 19, 2385

Page 5 is available in the electronic edition of the journal at http://www.aanda.org

Appendix A: Afterglow photometry

Table A.1. Log of the GROND observations, given in the AB system.

Time (s)	g'	r'	i'	z'
22 299	–	22.01 ± 0.38	–	21.73 ± 0.56
22 401	–	–	–	21.27 ± 0.40
22 503	–	22.09 ± 0.38	–	–
22 609	–	–	21.85 ± 0.40	21.41 ± 0.40
22 743	–	22.29 ± 0.33	–	21.45 ± 0.28
22 931	–	22.89 ± 0.57	22.16 ± 0.38	–
23 127	22.88 ± 0.56	22.73 ± 0.51	21.86 ± 0.35	–
23 313	–	22.91 ± 0.53	21.81 ± 0.34	–
23 639	22.90 ± 0.36	–	22.35 ± 0.31	22.09 ± 0.32
24 093	–	23.03 ± 0.29	22.18 ± 0.20	22.40 ± 0.45
24 540	–	22.49 ± 0.20	22.79 ± 0.45	–
24 984	22.88 ± 0.33	22.86 ± 0.31	22.53 ± 0.33	22.50 ± 0.36
25 443	–	22.62 ± 0.23	22.86 ± 0.39	–
25 889	23.07 ± 0.29	22.77 ± 0.24	22.98 ± 0.41	22.95 ± 0.45
26 335	23.45 ± 0.43	23.09 ± 0.32	–	21.95 ± 0.23
26 780	23.86 ± 0.50	22.71 ± 0.24	23.14 ± 0.27	–
27 234	23.54 ± 0.37	23.05 ± 0.25	22.50 ± 0.20	22.55 ± 0.29
27 679	23.41 ± 0.27	23.26 ± 0.21	22.58 ± 0.18	–
28 125	23.61 ± 0.33	23.23 ± 0.25	22.81 ± 0.26	22.88 ± 0.37
28 569	–	23.07 ± 0.24	22.76 ± 0.27	22.63 ± 0.31
29 024	23.52 ± 0.35	23.30 ± 0.31	22.84 ± 0.26	22.26 ± 0.24
29 475	23.43 ± 0.31	23.17 ± 0.25	22.97 ± 0.29	22.77 ± 0.40
29 922	–	23.19 ± 0.23	22.99 ± 0.33	–
30 375	–	23.11 ± 0.21	23.03 ± 0.29	22.98 ± 0.40
30 831	–	23.01 ± 0.20	22.91 ± 0.30	22.96 ± 0.46
31 275	23.70 ± 0.32	23.19 ± 0.23	23.23 ± 0.22	–
31 725	23.77 ± 0.34	23.25 ± 0.23	23.08 ± 0.20	22.56 ± 0.23
32 170	23.91 ± 0.31	23.48 ± 0.29	23.58 ± 0.41	–
32 628	23.75 ± 0.33	23.38 ± 0.25	23.01 ± 0.28	23.18 ± 0.46
33 077	23.50 ± 0.21	23.67 ± 0.30	23.26 ± 0.29	23.01 ± 0.29
33 524	–	23.52 ± 0.27	22.99 ± 0.15	–
34 369	24.46 ± 0.57	23.51 ± 0.26	23.83 ± 0.52	–
34 815	24.19 ± 0.31	24.07 ± 0.46	–	–
35 270	23.90 ± 0.31	23.74 ± 0.32	23.23 ± 0.29	23.44 ± 0.43
35715	24.21 ± 0.43	–	23.90 ± 0.57	23.11 ± 0.41

Notes. Data are not corrected for Galactic extinction.