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

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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
especially unique because it is among the most energetic events detected in the optical bands, but it is also established by the Nordic Optical Telescope (Olofsson et al. 2009) and confirmed by the VLT (Groot et al. 2009). Calibrations were performed using DAOPHOT and ALLSTAR tasks under IRAF (Tody 1993), similar to the procedure described in Krühler et al. (2008) and Yoldaşı et al. (2008). Calibrations were performed against the SDSS1. 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 $R_V = 3.1$.

2 http://www.astro.washington.edu/users/becker/hotpants.html
3 In the following we use the standard notation for the flux density, $F_\nu(t) \propto t^{-\alpha} v^\beta$.
4 A joint fit leads to the same conclusion but has a slightly higher $\chi^2_{\text{red}}$ of 0.59.

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 second epochs of the combined $g′r′i′z′$ images using HOTPANTS2. 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′′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 $\alpha_{\text{opt}} = 2.37 \pm 0.29$ ($\chi^2_{\text{red}} = 0.49$; 23 degrees of freedom)3. This slope also fits the $g′r′i′z′$ band data; i.e., the evolution of the optical afterglow was achromatic4. 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 $\nu_c$ lies above the X-ray band in the whole X-ray data set (De Pasquale et al. 2010).

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 Yoldaşı et al. (2008). Calibrations were performed against the SDSS1. 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 $R_V = 3.1$.

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De Pasquale et al. (2010) based on the X-ray light curve. Second, break had already occurred, and the evolution of the afterglow break decay slope is as steep as that. We conclude that at the time et al. 2010, 2011), we do not have a single case where the 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 $t_1 = 1.4$ ks (based on the X-ray data, De Pasquale et al. 2010) and $t_2 = 22$ 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 $a_3 = 2.4$ (Sect. 3.1), this gives an early-time slope of $a_1 = -0.2 \pm 0.2$ and $a_2 = 0.8 \pm 0.1$ (Fig. 4, blue dashed line). A relatively sharp break at $t_2$ 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. This solution suggests we interpret $t_2$ 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 ($a_{\text{opt}} \sim 1.1$) can be understood if, at the time when UVOT was observing, the injection frequency was (still) above the optical bands ($v_{\text{opt}} < v_{\text{jet}}$) and the afterglow was in the post-jet-break phase. While theoretically this suggests a decay slope of $a = 1/3$ (e.g., Zhang & Mészáros 2004), these authors argue that possibly the crossing of $v_{\text{jet}}$ 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 $a = p$, where $p$ is the power-law index of the electron distribution function, a steepening that is expected once $v_{\text{jet}}$ has passed through the optical bands. The GROND data now suggest re-evaluating this idea, since the expected steepening to $a = p$ 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 $a_1 = -0.2, a_2 = 1/3$, and $a_3 = 2.4$, 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

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5 In the second night GROND was observing between 116 ks and 122 ks after the burst. We do not see evidence of rebrightening.
factor of \( \sim 2\), 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 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 \( \nu_m \) 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 \( \nu_m \)) 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.

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

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**Notes.** Data are not corrected for Galactic extinction.