Letter to the Editor

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 $griz'$ 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

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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 (Oliveres 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; McBrein 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) detected so far in the entire GRB population (long plus short). Especially unique because it is among the most energetic events when compared to its X-ray light curve, its computed late-time evolution. 2.3 days after the trigger ($z$ = 0.903; Rau et al. 2009; McBrein et al. 2010).

When the Swift/XRT data are therefore consistent with having a spectral slope of $\alpha_{opt} = 2.37 ± 0.29$ ($\chi^2_{red} = 0.49$; 23 degrees of freedom$^1$). This slope also fits the $g'$/$r'$/$i'$ 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 ($\alpha_X = 2.18 ± 0.10$; 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.

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 $g'$-band light curve can be fit by a single power law with a slope of $\alpha_{opt} = 2.37 ± 0.29$ ($\chi^2_{red} = 0.49$; 23 degrees of freedom$^1$). This slope also fits the $g'$/$r'$/$i'$ 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 ($\alpha_X = 2.18 ± 0.10$; 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.
by GROND (De Pasquale et al. 2010) based on the X-ray light curve. Second, was in the post-jet break decay phase, confirming the finding of when the optical afterglow was monitored by GROND the 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 $v_{\text{jet}}$ 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 $\alpha = p$, 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 $\alpha = p$ 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 $\alpha_1 = -0.2 \pm 0.2$ and $\alpha_2 = 0.8 \pm 0.1$ (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 $\alpha_2$ 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 expected 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 ($\alpha_{\text{opt}} \sim 1.1$) 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 $\alpha = 1/3$ (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 $\alpha = p$, 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 $\alpha = p$ 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

\[ \alpha_1 = -0.2 \pm 0.2 \text{ and } \alpha_2 = 0.8 \pm 0.1 \text{ (Fig. 4, blue dashed line). A relatively sharp break at } t_2 \text{ is required (defined by } n_2) \text{ since the GROND data do not show evidence of any curvature in the light curve (Fig. 2). The UVOT two data points at 18 ks and 100 ks are strong outliers, however.} \]

\[ \alpha_1 = -0.2, \alpha_2 = 1/3, \text{ and } \alpha_3 = 2.4, \text{ fixed break times as mentioned before, as well as } n_1 = n_2 = 10. \text{ While this fit underpredicts the UVOT optical flux for } t < 2 \text{ ks by a} \]

In the second night GROND was observing between 116 ks and 122 ks after the burst. We do not see evidence of rebrightening.
As the injection frequency $\nu_{inj}$ across the optical bands, 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 $\nu_{inj}$) 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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## Appendix A: Afterglow photometry

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

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>$g'$</th>
<th>$r'$</th>
<th>$i'$</th>
<th>$z'$</th>
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<td>22 299</td>
<td>22.01 ± 0.38</td>
<td>-</td>
<td>21.73 ± 0.56</td>
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<tr>
<td>22 401</td>
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<td>-</td>
<td>21.27 ± 0.40</td>
<td></td>
</tr>
<tr>
<td>22 503</td>
<td>22.09 ± 0.38</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>22 609</td>
<td>-</td>
<td>21.85 ± 0.40</td>
<td>21.41 ± 0.40</td>
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<tr>
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<td>-</td>
<td>21.45 ± 0.28</td>
<td></td>
</tr>
<tr>
<td>22 931</td>
<td>22.89 ± 0.57</td>
<td>22.16 ± 0.38</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>23 127</td>
<td>22.88 ± 0.56</td>
<td>21.86 ± 0.35</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>23 313</td>
<td>22.91 ± 0.53</td>
<td>21.81 ± 0.34</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>23 639</td>
<td>22.90 ± 0.36</td>
<td>22.35 ± 0.31</td>
<td>22.09 ± 0.32</td>
<td></td>
</tr>
<tr>
<td>24 093</td>
<td>23.03 ± 0.29</td>
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<td>22.40 ± 0.45</td>
<td></td>
</tr>
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<td>22.79 ± 0.45</td>
<td>-</td>
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<td>22.50 ± 0.36</td>
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<tr>
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<td>22.62 ± 0.23</td>
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<tr>
<td>25 889</td>
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<td>22.77 ± 0.24</td>
<td>22.98 ± 0.41</td>
<td>22.95 ± 0.45</td>
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<tr>
<td>26 335</td>
<td>23.45 ± 0.43</td>
<td>23.09 ± 0.32</td>
<td>-</td>
<td>21.95 ± 0.23</td>
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<td>30 375</td>
<td>-</td>
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<td>23.03 ± 0.29</td>
<td>22.98 ± 0.40</td>
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<tr>
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<td>22.96 ± 0.46</td>
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<td>23.19 ± 0.23</td>
<td>23.23 ± 0.22</td>
<td>-</td>
</tr>
<tr>
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<td>23.25 ± 0.23</td>
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<tr>
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<tr>
<td>32 628</td>
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<tr>
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<td>-</td>
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**Notes.** Data are not corrected for Galactic extinction.