Swift Observations of GRB 081028

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1   Introduction

BAT triggered on GRB 081028 at 00:25:00 UT (Trigger 332851) (Guidorzi *et al.*, *GCN Circ.* 8421). This was a 128-s image-trigger on a long burst. XRT observations began at $T + 191$ s and discovered a bright and fading X-ray afterglow. UVOT began observing at $T + 200$ s and found no optical counterpart with the White filter down to 18 mag.

The optical afterglow was discovered by GROND 5.8 hours after the burst with a magnitude of 19.3 in the r' filter (Clemens *et al.*, *GCN Circ.* 8424). This was soon confirmed by the NOT (Olofsson *et al.*, *GCN Circ.* 8425). Remarkably, the X-ray and optical afterglow was seen to undergo a long-lasting late-time brightening from $\sim$9 ks on (Guidorzi *et al.*, *GCN Circ.* 8429) and Swift-UVOT detected it in the v, b and u-band filters (Schady & Guidorzi, *GCN Circ.* 8431). The optical and NIR brightening was confirmed with ground-based observations (Rumyantsev *et al.*, *GCN Circ.* 8455 ; Miller *et al.*, *GCN Circ.* 8499).

The spectroscopic redshift was measured with Magellan by Berger *et al.* (*GCN Circ.* 8434), who found $z = 3.038$ through the identification of several absorption features.

2   BAT Observations and Analysis

Using the data set from $T - 239$ to $T + 963$ s, the BAT ground-calculated position is RA(J2000) = 121.893 deg ($08^{\rm h}07^{\rm m}34.4^{\rm s}$), Dec(J2000)= +2.305 deg ($+02^{\rm d}18'16.8''$) with an uncertainty of 1.2 arcmin (radius, sys+stat, 90% containment). The partial coding was 85%.

The mask-weighted light curve shows two main peaks and a tail. The first peak starts at $\sim T + 20$ s, peaks at $\sim T + 80$ s, and falls to a minimum between the two peaks at $\sim T + 140$ s. The second peak peaks at $\sim T + 220$ s. There is a tail out to approximately $T + 400$ s. T_{90} (15–350 keV) is 260 ± 40 s (estimated error including systematics).

The time-averaged spectrum from $T + 29.3$ to $T + 441.5$ s is best fit by a power law with an exponential cutoff. This fit gives a photon index 1.25 ± 0.38, and $E_{\rm peak}$ of 58 ± 23 keV ($\chi^2/{\rm dof} = 57.6/56$). For this model the total fluence in the 15–150 keV band is $(3.7 \pm 0.2) \times 10^{-6}$ erg cm^{-2} and the 1-s peak flux measured from $T + 211.74$ s in the 15–150 keV band is 0.5 ± 0.1 ph cm^{-2} s^{-1}. A fit to a simple power law gives a photon index of 1.84 ± 0.09 ($\chi^2/{\rm dof} = 63.9/57$). All the quoted errors are at the 90% confidence level (Barthelmy *et al.*, *GCN Circ.* 8428).

The results of the batgrbproduct analysis are available at
http://gcn.gsfc.nasa.gov/notices_s/332851/BA/.

3   XRT Observations and Analysis

The XRT began observing GRB 081028 in Windowed Timing (WT) mode, 197 s after the BAT trigger. Using 5305 s of XRT Photon Counting (PC) mode data and 8 UVOT images, the astrometrically corrected X-ray position (using the XRT-UVOT alignment and matching UVOT field sources to the USNO-B1 catalogue) is found to be: RA(J2000)= 121.8948 deg ($08^{\rm h}07^{\rm m}34.76^{\rm s}$), Dec(J2000)= +2.3083 deg ($+02^{\rm d}18'29.8''$), with an uncertainty of 1.5 arcsec (radius, 90% confidence; Evans *et al.*,

GCN Circ. 8427).

The light-curve (Fig. 2), totalling 176 ks exposure and spanning from 197 to 8.6×10^5 s, shows a very complex evolution. In the first orbit data, covered entirely in WT mode, from 200 to $\sim$300 s it can be fit with a power law decay with an index of $\sim$0.5. This temporally coincides with the decay of the second peak observed by BAT, which peaked at 220 s (Barthelmy et $al.$, GCN Circ. 8428). Afterwards, there is flaring activity up to $\sim$400 s. From $\sim$400 to $\sim$700 s the afterglow undergoes a steep decay with a power-law index of about 3.4, followed by a large flare with a peak rate of $\sim$30 count s^{-1} and lasting longer than 150 s. First orbit data stopped during the peak of this flare. We fitted the curve from 4.1 ks on with the combination of a power-law, $F_1(t) \sim t^{-\alpha_1}$, and a smoothly broken power-law, $F_2(t) \sim 1/[(t/t_{\rm b})^{\alpha_2} + (t/t_{\rm b})^{\alpha_3}]$. From 4.1 to 8 ks the curve exhibits a steep decay, which is modelled by the single power-law, $\alpha_1 = 3.8 \pm 1.2$, with the count rate dropping to a value of $\sim$5 $\times 10^{-2}$ count s^{-1}, after which it experiences a long rebrightening with flaring activity, reaching a peak count rate of $\sim$0.3 count s^{-1}. We found the following remaining best-fitting parameters: $\alpha_2 = -2.1 \pm 0.3$ (power-law index of the rising part of the brightening), $t_{\rm b} = (22 \pm 2)$ ks (break time coinciding with the peak time in this case), $\alpha_3 = 2.1 \pm 0.1$ (final power-law index decay). Parameters' uncertainties are given at 90% confidence. The goodness of the fit is poor: $\chi^2/{\rm dof} = 206/156$ (P-value of 0.45%). Although the overall shape of the curve is reasonably fit by the model, this indicates the presence of significant variability on short time scales.

During the first orbit, the WT data spectrum undergoes a significant hard-to-soft evolution, with Γ changing from 1 to 3. A WT spectrum extracted during the steep decay from 400 to 700 s can be modelled with an absorbed power-law, with $\Gamma = 2.51 \pm 0.07$ and $N_{\rm H} = (8.0 \pm 1.1) \times 10^{20}$ cm^{-2}, in excess of the Galactic column density in this direction of 4.0×10^{20} cm^{-2}. The observed (unabsorbed) flux over this time interval is 7.8×10^{-10} (1.1×10^{-9}) erg cm^{-2} s^{-1}. A PC spectrum extracted from 5.0 to 23.2 ks can be modelled with an absorbed power-law, with $\Gamma = 2.25 \pm 0.16$ and $N_{\rm H} = (9.3 \pm 3.4) \times 10^{20}$ cm^{-2}. The observed (unabsorbed) flux over this time interval is 7.3×10^{-12} (1.0×10^{-11}) erg cm^{-2} s^{-1}.

Detailed light curves in both count rate and flux units are available in both graphical and ASCII formats at `http://www.swift.ac.uk/xrt_curves/`.

4 UVOT Observations and Analysis

The UVOT began settled observations of the field of GRB 081028 201 s after the BAT detection. No source was detected in any of the individual or coadded exposures in any of the UVOT filters at the XRT position (GCN Circ. 8427), or at the position of the reported optical counterpart (Clemens et $al.$, GCN Circ. 8424 ; Olofsson et $al.$,GCN Circ. 8425). The 3–σ upper limits at the position of the optical counterpart for the first white finding chart (fc) and in consequent co-added observations are reported in Table 1, where $T_{\rm start}$ and $T_{\rm stop}$ represent the elapsed time since the BAT trigger in seconds (Schady & Guidorzi, GCN Circ. 8430).

Furthermore, UVOT detected the optical counterpart in later UVOT observations, from 10 ks after the burst. This is suggestive of a re-brightening of the afterglow consistent with the time of the brightening observed in the XRT light curve (Guidorzi et $al.$, GCN Circ. 8429). The afterglow is detected in the v, b and u-band filters. The detection of the afterglow in the u-filter suggests a photometric upper limit on the redshift of z<3.2, in agreement with the spectroscopic value (Berger et $al.$, GCN Circ. 8434).

Table 1 reports UVOT photometry from early individual images. Figure 3 shows the UVOT light curves.

Magnitudes are not corrected for the Galactic extinction corresponding to a reddening of $E_{B-V} = 0.03$ mag (Schlegel et $al.$, 1998, ApJS, 500, 525). The photometry is on the UVOT photometric system described in Poole et $al.$ (2008, MNRAS, 383,627).
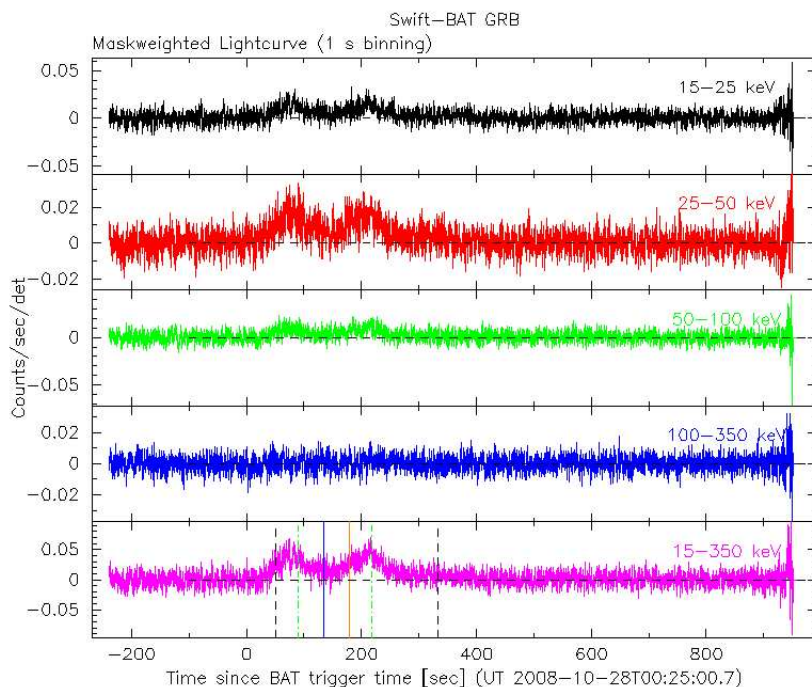
Figure 1: BAT Light curve. The mask-weighted light curve in the 4 individual plus total energy bands. The units are counts/s/illuminated-detector (note illum-det = 0.16 cm^2) and T_0 is 00:25:01 UT.
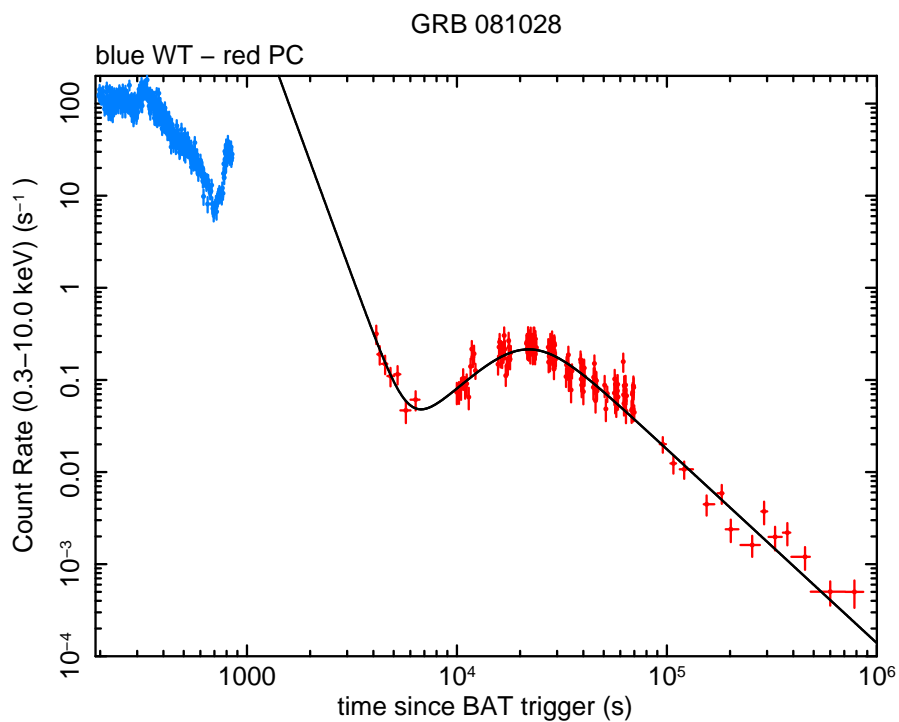

Figure 2: XRT Light curve. Flux in the 0.3-10 keV band: Windowed Timing (blue) and Photon Counting (red) modes. The approximate conversion is 1 count s$^{-1} \sim 3.5 \times 10^{-11}$ erg cm^{-2} s^{-1}.

Filter	T_{start} (s)	T_{stop} (s)	Exposure (s)	Mag
white	201	350	146	>20.95
white	481	846	58	>20.05
v	357	722	58	>18.50
b	456	821	58	>19.33
u	432	796	58	>18.98
uvw1	407	771	58	>19.01
uvm2	382	746	58	>18.70
uvw2	506	868	55	>19.01
v	4050	5684	393.2	>20.13
v	10740	28995	1770.3	20.23 ± 0.19
b	4870	6504	393.3	>20.79
b	17436	35567	1433.5	20.19 ± 0.14
u	4665	6299	393.2	>20.53
u	16524	34778	2539.8	21.21 ± 0.26
uvw1	4460	6094	393.2	>20.61
uvw1	15618	33865	2656.7	>21.89
uvm2	4255	5889	393.2	>20.51
uvm2	21399	29784	2428.5	>21.66
uvw2	5281	5480	196.6	>20.23
uvw2	29001	28082	1771.2	>20.61

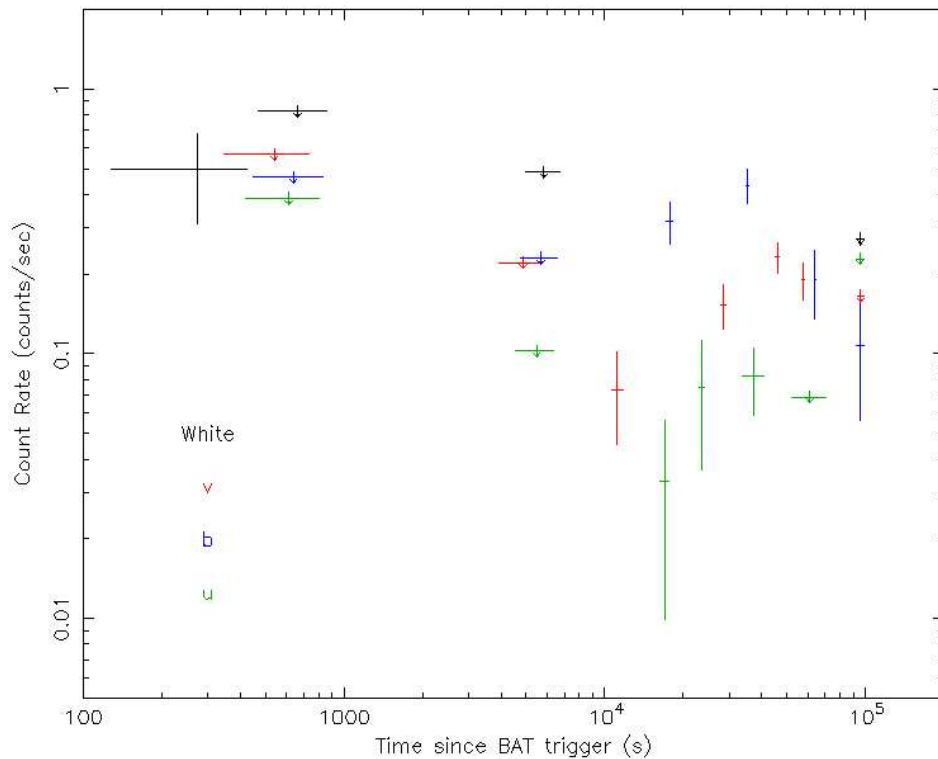Table 1: Magnitudes from UVOT observations. Upper limits are given at 3σ confidence.

Figure 3: UVOT Light curve.