

## Optical/UV afterglows: Swift UVOT overview

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The ultraviolet and optical telescope (UVOT) on Swift provides coverage of gamma-ray bursts and their afterglows in the 170–650 nm band, yielding multiwavelength data of considerable diagnostic power in conjunction with the Swift X-ray Telescope. The results from the first eighteen months of operation show a broad range of afterglow behaviour, with considerably more complexity in many bursts than would be expected from the simple fireball model for the explosion. We briefly illustrate the capabilities of UVOT for measuring the evolution of nearby supernovae by reference to the observations of GRB 060218, and discuss the peculiar case of GRB 060614, which apparently resides in a nearby galaxy but which did not show the expected supernova feature in its light curve due to radioactive nickel decay. We discuss how the combination of X-ray and UV/optical spectral data can be used to investigate the environment of GRB host galaxies.

**Keywords:** gamma rays; bursts; ISM; dust; extinction

### 1. Introduction

The study of optical afterglows of gamma-ray bursts (GRB) can reveal much about the physical processes that power these events and the environment in which they are produced. The form of the afterglow decay conveys information about the energetics of the fireball, for example, by revealing the spectral evolution of the so-called cooling break (Zhang & Mészáros 2004). Similarly, the opening angle of the relativistic jet can be constrained by timing the achromatic break that is expected when the relativistic beaming angle of the decelerating jet exceeds the jet opening angle (Sari *et al.* 1999). The slope of the afterglow decay, and any variability over and above a monotonic decrease, can signal jet structure or ongoing activity in the central engine. Monitoring of the late-time light curve may reveal evidence for a supernova explosion, while study of the host galaxy of the burst provides clues to the burst environment and can be used to determine its redshift. The spectral slope of the afterglow emission is also an important diagnostic. It is linked, through the energy spectrum of the relativistic

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electrons, to the slope of the afterglow decay in the standard fireball model (Zhang & Mészáros 2004) and provides a test of the burst physics and the nature of the surrounding environment. Deviations of the spectrum from a simple form also convey environmental information by revealing the degree of obscuration by material in the host galaxy and giving clues to its chemical composition.

The ultraviolet and optical telescope (UVOT) on the Swift Gamma-ray Burst observatory is used to monitor GRB and their afterglows in the 170–650 nm band (Roming *et al.* 2005). The UVOT has a 0.3 m diameter optical aperture and a field of view of 17 arcmin on a side. It uses a photon-counting detector that has half arcsec pixels, and can observe the sky through a series of six filters that span the wavelength range of the instrument, three in the near UV with central wavelengths of 190 nm, 220 nm and 260 nm, and three covering the *U*, *B* and *V* optical bands. There is also a white light filter for maximum sensitivity to faint bursts, and this can achieve a sensitivity of  $B=24$  in a 1000 s exposure. UVOT provides sensitivity to un-reddened bursts up to a redshift of about 5, and can be used to determine an approximate burst redshift by constraining the wavelength of the Lyman cut-off within its broad-band filters. The rapid response of Swift means that UVOT can deliver sub-arcsecond burst positions within minutes of the burst onset. One of the major strengths of Swift is the ability to observe afterglows simultaneously in the optical/UV and X-ray bands using UVOT and XRT, providing multiwavelength coverage that greatly enhances the diagnostic potential of the data.

## 2. Light curves

There is considerable variety among the burst light curves measured using UVOT with a range of behaviour with respect to decay slope and structure, flares and variability, and the degree of correspondence with features seen in the X-ray band.

GRB050525A was a bright burst at a redshift of 0.606 that was observed in detail with Swift (Blustin *et al.* 2006; Mason *et al.* 2006*a,b*). The underlying X-ray power-law decay slope is initially  $-1.2$ , though there is evidence for excess flux starting approximately 300 s after the GRB trigger, which suggests a minor flare. The decay slope breaks to  $-1.62$  after approximately 10 000 s. The optical decay is initially steeper than in the X-ray band, before flattening to a value that is shallower. Specifically, the UVOT data can be fit with a combination of two power-laws that have slopes of  $-1.56$  and  $-0.6$ , respectively. Beyond 10 000 s, the optical decay steepens in line with the X-ray curve to a slope of about  $-1.6$ .

Overall, the behaviour of GRB050525A can be convincingly described by a standard fireball model with an achromatic jet break starting at about  $10^4$  s. The initial steep slope of the optical curve can be ascribed to emission from a forward shock, while the spectral evolution prior to the jet break marks the migration of the cooling frequency through the UV and optical range. The combination of the jet-break time and the isotropic equivalent energy emitted in the burst leads to an estimate of the jet opening angle between  $3.2$  and  $5^\circ$  depending on how the jet break is modelled, with the actual flux emitted by the burst lying between  $3.6 \times 10^{49}$  and  $1.0 \times 10^{50}$  ergs.

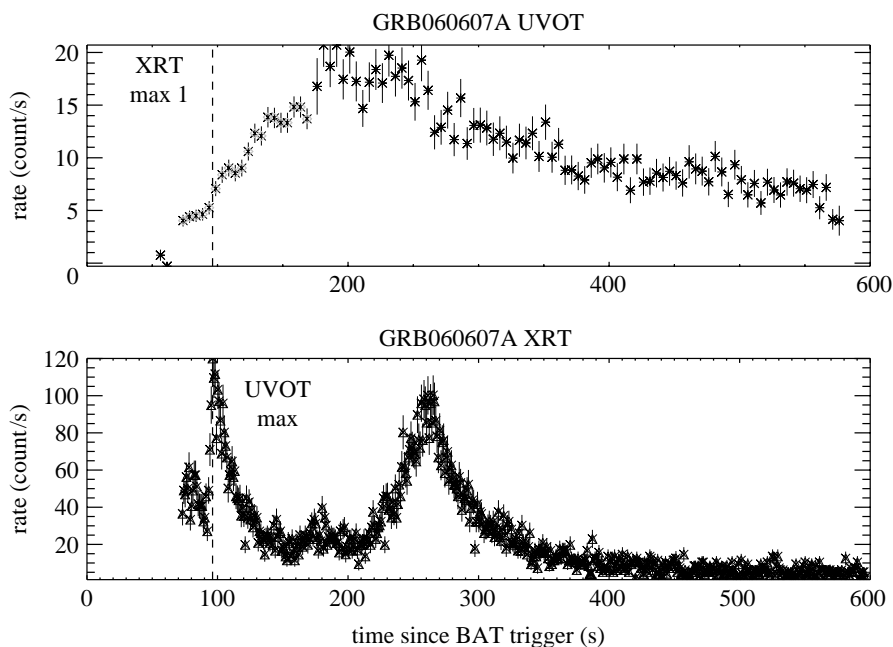


Figure 1. Light curve of GRB 060607A in the first 600 s following the burst trigger. The top panel shows the light curve measured with UVOT in the white light filter (light symbols) and the V-band filter (heavy symbols), normalized to a common scale. The lower panel shows the X-ray light curve measured with XRT during the same interval.

Other burst afterglow behaviour is not so easily interpreted. Some, which include GRB050319 (Cusumano *et al.* 2006; Mason *et al.* 2006a), GRB050401 (de Pasquale *et al.* 2006) and GRB050922C (Hunsberger *et al.* 2005) show a much shallower decay than can be comfortably explained by the standard fireball model on the basis of their spectral slope. The origin of this behaviour may lie in the continued injection of energy into the shock, either because of ongoing, but decreasing, activity of the central engine (Zhang & Mészáros 2004; Mason *et al.* 2006a) or because the initial ejecta-contained material with a range of Lorentz Factors (de Pasquale *et al.* 2006). In the case of GRB 050319, there is a break in the X-ray slope from a value of  $-0.5$  to  $-1.14$  after  $2.6 \times 10^4$  s (Cusumano *et al.* 2006), the latter slope being more in line with expectations for a ‘standard’ fireball. However, the optical data continues beyond this point with the initial shallow decay slope of  $-0.5$  (Mason *et al.* 2006a). Similar behaviour is seen in GRB 050802, where the X-ray slope breaks from  $-0.6$  to  $-1.6$  after about  $10^4$  s, but the optical decay continues with a slope of  $-0.8$  (Oates *et al.* in press).

Variability in the form of flares is common in the early X-ray emission of GRB afterglows as discussed elsewhere in this volume, though these flares are generally not seen in the optical band. Nevertheless, there are instances where there is marked optical variability as well. An example is GRB 060206 (Boyd *et al.* in preparation), where there is a substantial re-brightening of the optical flux some 5000 s after the burst trigger. This is also seen in the X-ray band. In contrast, the optical flux of GRB 060607A, shown in figure 1, brightens gradually in the first 200 s following the GRB trigger, while the light curve in X-rays

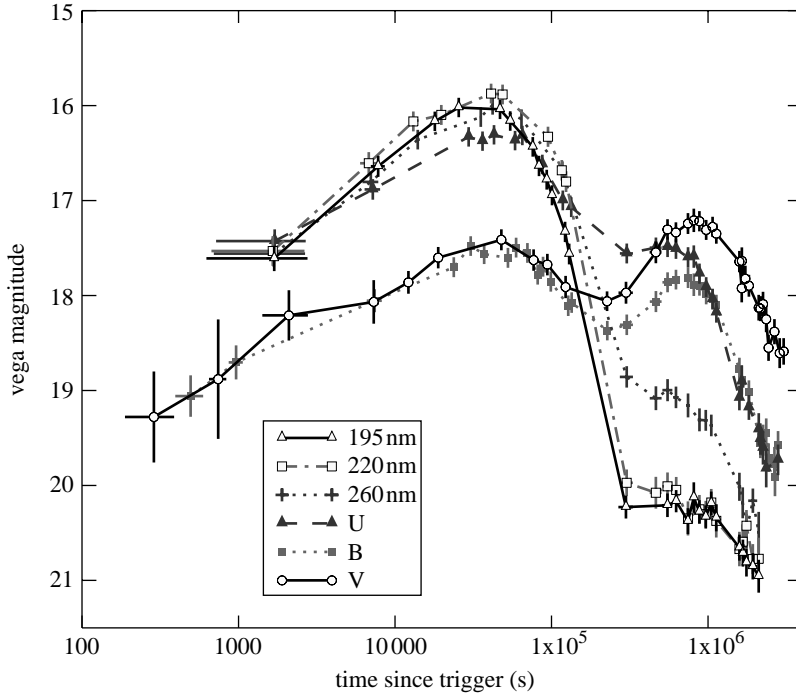


Figure 2. Light curve of GRB060218/SN2006aj in the six UVOT broadband filters. The three ultraviolet filters (designations UVW1, UVM2 and UVW2) have approximate central wavelengths of 260, 220 and 195 nm, respectively.

is totally different and is dominated by two very large flares. Similar behaviour is seen during the first 1000 s of the afterglow evolution in GRB 050730 (Pandey *et al.* 2006).

### 3. GRB060218/SN2006aj

GRB060218 was a long ( $T_{90} \sim 2100$  s) GRB at a redshift of  $z=0.033$  (Campana *et al.* 2006). Three days after the GRB, the optical signature of an emerging Supernova of type Ic (i.e. with no emission lines of hydrogen and helium) was detected (Pian *et al.* 2006). This is the first time that a nearby supernova explosion has been monitored intensively from the onset of the GRB and the data supply hitherto inaccessible detail of the phenomenology of the explosion.

The UVOT data (figure 2) show a source that brightens systematically over the first half day following the GRB, peaking at a (Vega) magnitude of about 16 in the ultraviolet near 200 nm, and about 17.8 in the V band. There is a second peak, which is particularly prominent in the optical filters, about 10 days after the explosion. The initial peak is thought to be due to the breakout of a shock driven into the circumstellar material by a mildly relativistic shell (Campana *et al.* 2006), whereas the second peak, a characteristic of supernova light curves, is due to radioactive heating of the ejecta. The shock breakout interpretation is supported by the spectrum, which evolves with time in a manner consistent with an expanding and cooling shell. There is evidence for a thermal component (soft

X-ray excess) in the X-ray spectrum initially, which increases in luminosity as time passes consistent with the expected behaviour of an expanding optically thick shell. This then shifts into the ultraviolet and is picked up by the UVOT. By about 1.3 days after the GRB, the peak of the blackbody emission is within the UVOT passband. A fit of a blackbody spectral model gives a temperature of  $kT = 3.7_{-0.9}^{+1.9}$  eV (43 000 K) and a radius of  $3.29_{-0.93}^{+0.94} \times 10^{14}$  cm, indicating an expansion velocity of about  $30\,000 \text{ km s}^{-1}$ .

#### 4. GRB 060614

GRB 060614 (Gehrels *et al.* in press) was a long burst ( $T_{90} = 102$  s), which is positionally coincident with a faint dwarf galaxy at a redshift of 0.125. At this low redshift, the burst was a prime candidate for an associated supernova event, but none was detected to a limit 100 times lower than the previous detections (Gal-Yam *et al.* in press). Moreover, a close examination of the morphology and spectrum of the Swift Burst Alert Telescope (BAT) light curve shows an initial hard spectrum event lasting about 5 s, followed by a softer more extended phase lasting about 100 s. The lack of a supernova and the hard spectrum of the initial event are reminiscent of the ‘short’ class of bursts, leading to suggestions that this is an object that spans the accepted long-burst/short-burst class divide. This is supported by a comparison of the time-lag between different energy bands in the BAT light curve and the inferred peak luminosity of the burst, which falls within the region of the distribution populated by short bursts (Gehrels *et al.* in press).

Schaefer & Xiao (in press) have argued, however, that the apparent inconsistencies in the behaviour of GRB 060614 can be resolved if the association with the  $z = 0.125$  galaxy is a line-of-sight coincidence, and that the burst actually occurred at much greater distance. Based on consideration of various luminosity indicators, they deduce that the burst redshift must be greater than 1.4. At this redshift, however, the Lyman cut-off at  $912 \text{ \AA}$  would be redshifted into the UVOT sensitivity band. The combined UVOT and XRT spectral data for this burst (interpolated to a common epoch) are shown in figure 3 and exhibit no evidence for such a cut-off. A fit to the combined data, allowing for reddening and absorption both in the host galaxy and in the Milky Way, rejects any redshift above 1 (figure 4), thus eliminating the Schaefer and Xiao explanation of the peculiar properties of GRB 060614.

The UVOT light curve of GRB 060614 is, at the same time, unlike anything that has been seen from short bursts. It is visible for a long time, and is essentially constant at  $U \sim 18.8$  for the first 14 h after the GRB, before fading slowly (analysis by Holland & Brown). It is still detected above background 10 days after the GRB. This lends credence to the idea that this is a supernova-type event, but one where the  $^{56}\text{Ni}$  powered heating of the ejecta, which normally produces an optical peak after about 10 days, is absent.

#### 5. GRB host galaxy environment

The combination of XRT and UVOT can be used to determine the spectral energy distribution of GRB afterglows and search for signatures of absorption and reddening imprinted on the spectrum, which convey information on the host

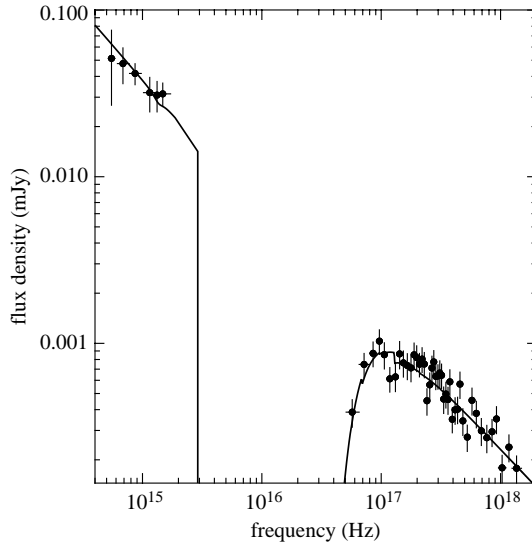


Figure 3. Multiwavelength spectrum of GRB 060614 combining UVOT and XRT data interpolated to a common epoch. The best fit model is shown as a solid line, which includes absorption and reddening at the rest wavelength of the host galaxy and due to the Milky Way.

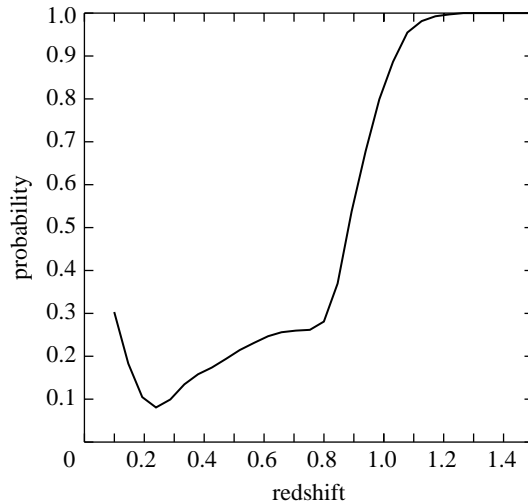


Figure 4. Probability at which a given redshift is rejected for the model fit to the GRB 060614 spectrum.

galaxy environment in which the burst is produced. *Schady et al. (in press)* have analysed seven bright bursts which are at low enough redshift to be detected significantly in at least three UVOT filters (in order to define the optical/UV spectral shape). They fit X-ray absorption components and optical/UV reddening at the redshift of the host galaxy and due to the Milky Way. Three different reddening laws are tried for the host galaxy, being those determined for the Milky Way galaxy, the Large Magellanic Cloud (LMC) and the Small

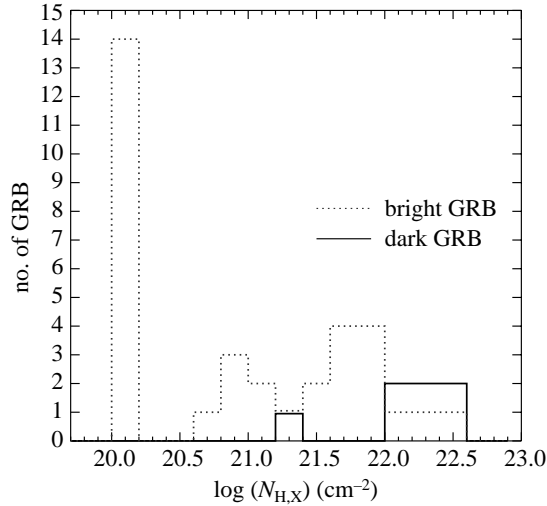


Figure 5. Distribution of measured X-ray column density for bursts with a UVOT counterpart (bright bursts) and bursts that are only seen at wavelengths above the UVOT sensitivity band (dark bursts).

Magellanic Cloud (SMC). These differ primarily in the prominence of the 220 nm absorption feature, which is most marked in the Milky Way, and the proportion of far-UV absorption, which is greatest in the SMC.

Of the seven afterglows examined, four are significantly better fitted by an SMC or LMC model than the reddening law of the Milky Way. Specifically, there is no evidence for a 220 nm absorption feature at the rest-wavelength of the host galaxy in any of these bursts. These are GRB 050318, GRB 050525A, GRB 051111 and GRB 060512. A fifth, GRB 050802, conversely does show evidence for a 220 nm feature and is best fitted by a Milky Way model. In the other cases, GRB 050824 and GRB 060418, the reddening is too low to be sensitive to the difference between models. This suggests that the majority, but not all, of the bursts occur in chemically un-evolved environments.

The data also give estimates of the ratio of gas-to-dust by comparison of the X-ray absorption column with the degree of optical/UV reddening. Allowing for the different overall relative abundance of heavy elements in the LMC and SMC (taken to be one-third and one-eighth, respectively of the Milky Way), the majority of the Swift data clusters around the typical gas-to-dust ratio of these galaxies. This contrasts with pre-Swift work which suggested that a higher gas to dust ratio was the norm for GRB environments, albeit with large uncertainties. One Swift GRB afterglow, that of GRB 051111, does however have a gas-to-dust ratio significantly higher than the rest of the sample.

Schady *et al.* (in press) also compare the best fit X-ray column density of bursts that have a UVOT optical counterpart, with those that do not. All these burst have to have a measured redshift, and thus an optical/IR counterpart, to be useful, and those in the sample not detected by UVOT have optical counterparts at wavelengths beyond the V-band, which is the reddest filter covered by UVOT. The X-ray column of the sample not detected by UVOT is systematically higher than the sample that is detected by UVOT (figure 5).

We estimate that the significance of this result is greater than  $3\sigma$  based on the *a priori* probability of drawing, at random, a sample of six bursts from the combined distribution that have a mean column as extreme as observed. This result is consistent with the idea that at least some fraction of so-called dark bursts, those that have no detected optical afterglow, are simply located in regions of high reddening.

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