

Shock break-out: how a GRB revealed the beginnings of a supernova

BY ALEXANDER J. BLUSTIN*

*UCL Mullard Space Science Laboratory, Holmbury St Mary, Dorking,
Surrey RH5 6NT, UK*

In February 2006, Swift caught a gamma-ray burst (GRB) in the act of turning into a supernova, and made the first ever direct observations of the break-out and early expansion of a supernova shock wave. GRB 060218 began with an exceptionally long burst of non-thermal gamma-rays, lasting over 2000 s, as a jet erupted through the surface of the star. While this was in progress, an optically-thick thermal component from the shock wave of the supernova explosion grew to prominence, and we were able to track the mildly relativistic expansion of this shell as the blackbody peak moved from the X-rays into the UV and optical bands. The initial radius of the shock implied that it was a blue supergiant that had exploded, but the lack of hydrogen emission lines in the supernova spectrum indicated a more compact star. The most likely scenario is that the shock ploughed into the massive stellar wind of a Wolf–Rayet progenitor, with the shock breaking-out and becoming visible to us once it reached the radius where the wind became optically-thin. I present the Swift observations of this landmark event, and discuss the new questions and answers it leaves us with.

Keywords: gamma rays; bursts; supernovae; individual (SN 2006aj); stars; Wolf–Rayet; shock waves

1. Introduction

The gamma-ray burst (GRB) detected by the Swift (Gehrels *et al.* 2004) Burst Alert Telescope (BAT; Barthelmy *et al.* 2005) during a slew on 18 February 2006 looked unusual right from the beginning. The initial burst of γ -rays was both exceptionally long ($T_{90} = 2100 \pm 100$ s) and peaked at a very low energy ($4.9^{+0.4}_{-0.3}$ keV), the latter of which classifies the event as an X-ray flash. At the red shift of the event, $z = 0.03345 \pm 0.0006$ (Mirabal *et al.* 2006) making it the second closest GRB yet detected, its isotropic equivalent energy was $E_{\text{iso}} = 6 \times 10^{49}$ erg, which is 100–1000 times less than most GRBs. By way of comparison, GRB 980425, the first GRB to be identified with a supernova, had a much shorter T_{90} of 23.3 ± 1.4 s (Galama *et al.* 1998), a higher E_{peak} of 55 ± 21 keV, and a lower E_{iso} of $(1.0 \pm 0.2) \times 10^{48}$ erg (Amati 2006).

During the first 3000 s of the Swift observation of GRB 060218 (figure 1), the 0.3–10 keV X-ray lightcurve from the X-ray telescope (XRT; Burrows *et al.* 2005) shows a smooth peak and gradual decay, while after 3000 s the optical

*ajb@mssl.ucl.ac.uk

One contribution of 35 to a Discussion Meeting Issue ‘Gamma-ray bursts’.

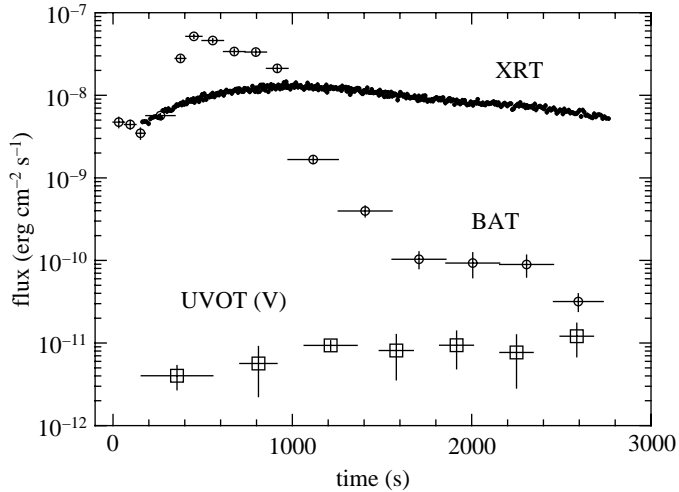


Figure 1. γ -ray (BAT), X-ray (XRT) and V-band (UVOT) lightcurves from the first orbit (approx. 3000 s) of Swift observations of GRB060218 (after [Campana et al. 2006](#)). The BAT flux is calculated by fitting XRT and BAT data together, so the BAT flux is dominated by the extrapolation of the XRT fit into the BAT energy range.

V-band flux observed with the UV/optical telescope (UVOT; [Roming et al. 2005](#)) is still rising. The exponentially decaying X-ray lightcurve gives way to a power-law decay of the type more typically seen in GRB afterglows, 10 ks after the beginning of the burst ([figure 2a](#)). The optical/UV flux registered by the UVOT ([figure 2b](#)) rises to a UV dominated peak at approximately 40 ks, and later on to a peak dominated by optical light at 600 ks. All of this unusual phenomenology offers clues as to the nature of the progenitor and the physical evolution of the event, which I will discuss in the following sections. These observations and their interpretation are presented in greater detail by [Campana et al. \(2006\)](#).

2. The progenitor

The early behaviour of the X-ray emission gives us information about the progenitor. The X-ray spectrum compiled from data taken during the first 3 ks shows ([figure 3](#)) that there is a thermal component to the emission as well as the power-law typically observed in GRB spectra. The flux in this thermal component evolves with time; its flux is plotted alongside the total X-ray flux in [figure 2a](#). The thermal flux dominates the X-ray emission between approximately 2 and 8 ks after the beginning of the event, but dies away exponentially after that point. Fitting a blackbody model to this thermal emission using XSPEC, we obtained a temperature of $kT \approx 0.17$ keV. The characteristic radius R_{shell} of the emitting region can be estimated as

$$R_{\text{shell}} \approx \left(\frac{E_{\text{iso}}}{aT^4} \right)^{1/3}, \quad (2.1)$$

where E_{iso} is the equivalent isotropic power of the GRB; a is the radiation density constant; and T is the thermal temperature. The resulting radius, approximately 5×10^{12} cm, would imply a blue supergiant progenitor, but the lack of hydrogen

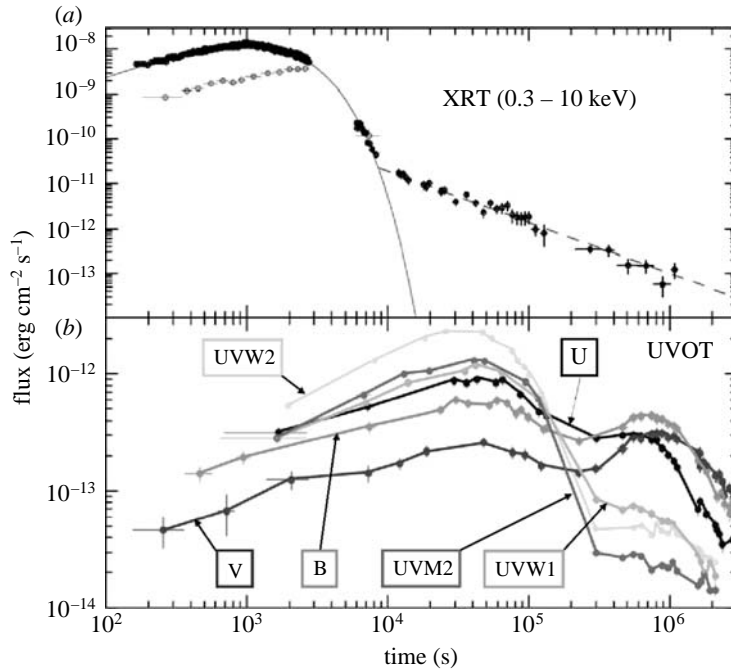


Figure 2. (a) X-ray lightcurve of GRB060218, 0.3–10 keV, (black circles) with the contribution of the thermal component (grey circles); (b) UVOT lightcurves in the six colour filter bands: V (centred at 5440 Å), B (4390 Å), U (3450 Å), UVW1 (2510 Å), UVM2 (2170 Å) and UVW2 (1880 Å) (after Campana *et al.* 2006).

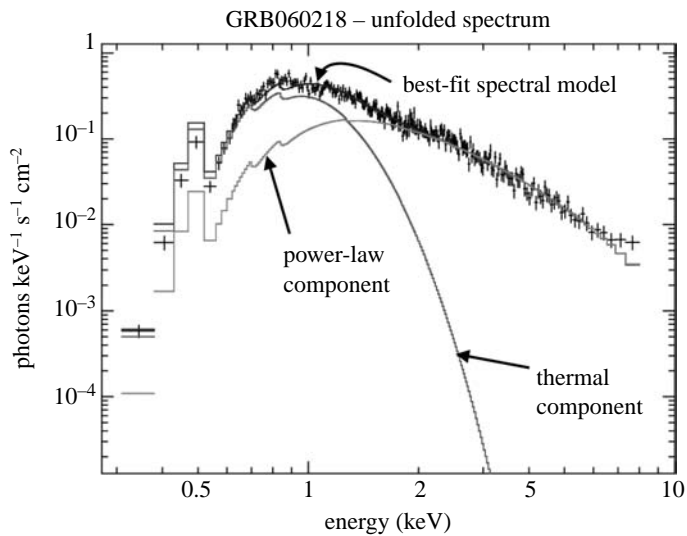


Figure 3. X-ray spectrum of GRB060218, 0.3–10 keV, compiled from data taken up to approximately 3 ks after the beginning of the event, with the best fitting spectral model superimposed on the data. The thermal and power-law components are also plotted.

lines in the optical spectra of the supernova (e.g. Mazzali *et al.* 2006) implies a more compact star. The larger apparent radius can, however, be explained by the presence of a massive stellar wind. Assuming that the early expansion of the emitting region was linear, due to light-travel-time effects, we can estimate an initial progenitor radius of $(4 \pm 1) \times 10^{11}$ cm. This size, and the presence of the optically thick stellar wind, implies that the progenitor was a Wolf–Rayet star.

3. The shockwave

The shockwave of the explosion becomes visible when it reaches the radius where the wind becomes optically thin. The shock is probably non-spherical, since the characteristic radius R_{shell} , which is calculated on the assumption of spherical symmetry, is larger than the radius of the blackbody as fitted to the XRT data. This may be due to the presence of the presumed GRB jet or perhaps to the stellar wind being non-spherical. Since we actually observe the process of the shock breaking-out of the stellar wind, we can constrain the delay between the GRB and supernova start to be less than 4 ks.

The shock compresses the wind to a thin shell. The optical depth of the shell must be about 1, so we can obtain its opacity, estimate the mass of the shell and therefore the wind mass-loss rate \dot{M} .

$$\dot{M} \sim \left(\frac{M_{\text{shell}} v_{\text{wind}}}{R_{\text{shell}}} \right), \quad (3.1)$$

where we take $v_{\text{wind}} = 10^8$ cm s⁻¹, a typical value for Wolf–Rayet stars. We obtain $\dot{M} \sim 3 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$, and using the radius R_{shell} , the wind density $\rho_{\text{wind}} \sim 10^{12}$ g cm⁻³. The thermal energy density behind a radiation-dominated shock is

$$aT_{\text{BB}}^4 \sim 3\rho_{\text{wind}} v_{\text{shock}}^2, \quad (3.2)$$

where T_{BB} is the blackbody temperature and v_{shock} is the shock speed. Using ρ_{wind} that we have calculated, $v_{\text{shock}} \approx c$.

4. The stellar remnant

At the UV emission peak observed with the UVOT, the blackbody emission in the UV and optical is far higher than that expected from the shock. Instead, the emission is probably from the expanding stellar remnant. The expansion of the remnant is traced by the evolution of the broad-band UVOT spectrum, as shown in figure 4. At the time of the earliest spectrum in the figure, 32 ks (figure 4a), the peak of the blackbody is still far higher than the UVOT band, and so the UVOT spectrum consists of the Rayleigh–Jeans tail of the blackbody, which is cut into by intrinsic extinction in the GRB host. This allows us to fit the depth of the extinction, which is then fixed in subsequent fits of the blackbody parameters. Using the *z_{dust}* model in XSPEC, we obtain an intrinsic $E(B - V) = 0.20 \pm 0.03$, assuming an SMC reddening law (Pei 1992).

One hundred and twenty kiloseconds after the beginning of the event (figure 4b), the blackbody peak is centred in the UVOT band and so its temperature and radius can be fitted. We obtain $kT \sim 3.7_{-0.9}^{+1.9}$ eV and $R_{\text{BB}} = 3.29_{-0.93}^{+0.94} \times 10^{14}$ cm.

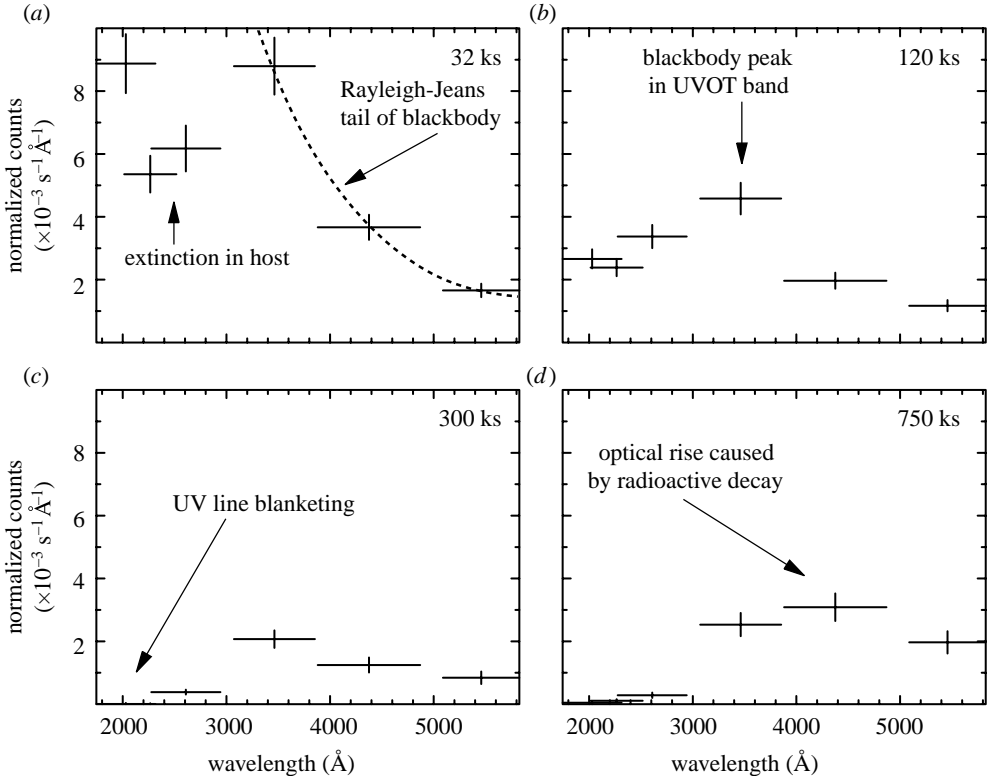


Figure 4. The evolution of the UVOT broad-band spectrum from 32 to 750 ks after the beginning of the event. The data points represent the count rate per Ångström in each of the UVOT filters (note that the instrumental response has not been removed in these plots): left to right: UVW2 (centred at 1880 Å), UVM2 (2170 Å), UVW1 (2510 Å), U (3450 Å), B (4390 Å) and V (5440 Å).

This radius implies an expansion speed of $27\,000 \pm 8000 \text{ km s}^{-1}$, consistent with the speeds obtained from optical spectroscopy (e.g. Mazzali *et al.* 2006; Pian *et al.* 2006; Sollerman *et al.* 2006). By 300 ks (figure 4c), the remnant has cooled to the extent that elements can combine, and so the UV flux is drastically decreased from that point on by line blanketing. Finally, at 750 ks (figure 4d), the optical band has re-brightened due to radioactive decay in the supernova remnant.

5. Conclusions

Our conclusions are, then, that the progenitor of GRB060218/SN2006aj was a Wolf–Rayet star, and that the one-of-a-kind lightcurves obtained with Swift signify the breakout of the shockwave from the dense stellar wind of the progenitor, and the expansion and cooling of the stellar remnant.

This unusual event was followed up by many other telescopes and observers, leading to a range of novel possibilities and conclusions. First, the probable approximately $20M_{\odot}$ mass of the progenitor was low enough for a magnetar remnant—rather than a black hole—to have formed, leading to the intriguing suggestion that X-ray flashes are the magnetic activity of magnetars forming

from the implosion of low mass progenitors, while GRBs signal the collapse of high mass stars and the formation of black holes (Mazzali *et al.* 2006; Soderberg *et al.* 2006). The presence or otherwise of relativistic ejecta or a collimated jet may also be a fundamental distinction between supernovae accompanied by GRBs, and those that are not (Pian *et al.* 2006; Soderberg *et al.* 2006). Whatever the compact remnant is, the long duration of the afterglow is a sign of continuing activity of a rapidly spinning central engine (Fan *et al.* 2006; Soderberg *et al.* 2006). The fact that this low-luminosity event was even detected implies that there is a much larger number of such events than previously thought; perhaps, even that they are the most common high-energy transient events in the Universe (Cobb *et al.* 2006; Pian *et al.* 2006).

References

- Amati, L. 2006 The $E_{\text{p,i}}-E_{\text{iso}}$ correlation in gamma-ray bursts: updated observational status, re-analysis and main implications. *Mon. Not. R. Astron. Soc.* **372**, 233–245. (doi:10.1111/j.1365-2966.2006.10840.x)
- Barthelmy, S. D. *et al.* 2005 The burst alert telescope (BAT) on the Swift midex mission. *Space Sci. Rev.* **120**, 143–164. (doi:10.1007/s11214-005-5096-3)
- Burrows, D. N. *et al.* 2005 The Swift X-ray telescope. *Space Sci. Rev.* **120**, 165–195. (doi:10.1007/s11214-005-5097-2)
- Campana, S. *et al.* 2006 The association of GRB 060218 with a supernova and the evolution of the shock wave. *Nature* **442**, 1008–1010. (doi:10.1038/nature04892)
- Cobb, B. E., Baily, C. D., van Dokkum, P. G. & Natarajan, P. 2006 SN 2006aj and the nature of low-luminosity gamma-ray bursts. *Astrophys. J.* **645**, L113–L116. (doi:10.1086/506271)
- Fan, Y.-Z., Piran, T. & Xu, D. 2006 The interpretation and implication of the afterglow of GRB 060218. *J. Cosmol. Astropart. Phys.* **JCAP09**, 13. (doi:10.1088/1475-7516/2006/09/013)
- Galama, T. J. *et al.* 1998 An unusual supernova in the error box of the γ -ray burst of 25 April 1998. *Nature* **395**, 670–672. (doi:10.1038/27150)
- Gehrels, N. *et al.* 2004 The Swift gamma-ray burst mission. *Astrophys. J.* **611**, 1005–1020. (doi:10.1086/422091)
- Mazzali, P., Deng, J., Nomoto, K., Sauer, D. N., Pian, E., Tominaga, N., Tanaka, M., Maeda, K. & Filippenko, A. V. 2006 A neutron-star-driven X-ray flash associated with supernova SN 2006aj. *Nature* **442**, 1018–1020. (doi:10.1038/nature05081)
- Mirabal, N., Halpern, J. P., An, D., Thorstensen, J. R. & Terndrup, D. M. 2006 GRB 060218/SN 2006aj: a gamma-ray burst and prompt supernova at $z=0.0335$. *Astrophys. J.* **643**, L99–L102. (doi:10.1086/505177)
- Pei, Y. C. 1992 Interstellar dust from the Milky Way to the Magellanic Clouds. *Astrophys. J.* **395**, 130–130. (doi:10.1086/171637)
- Pian, E. *et al.* 2006 An optical supernova associated with the X-ray flash XRF 060218. *Nature* **442**, 1011–1013. (doi:10.1038/nature05082)
- Roming, P. W. A. *et al.* 2005 The Swift ultra-violet/optical telescope. *Space Sci. Rev.* **120**, 95–142. (doi:10.1007/s11214-005-5095-4)
- Soderberg, A. M. *et al.* 2006 Relativistic ejecta from X-ray flash XRF 060218 and the rate of cosmic explosions. *Nature* **442**, 1014–1017. (doi:10.1038/nature05087)
- Sollerman, J. *et al.* 2006 Supernova 2006aj and the associated X-ray flash 060218. *Astron. Astrophys.* **454**, 503–509. (doi:10.1051/0004-6361:20065226)