Mon. Not. R. Astron. Soc. **382,** L77–L81 (2007) doi:10.1111/j.1745-3933.2007.00396.x

Did we observe the supernova shock breakout in GRB 060218?

G. Ghisellini,⋆ G. Ghirlanda and F. Tavecchio
Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807 Merate, Italy

Accepted 2007 September 14. Received 2007 September 12; in original form 2007 July 4

ABSTRACT

The early optical data of GRB 060218 (the first 10^5 s after the trigger) have been interpreted as blackbody emission associated with the shock breakout of the associated supernova. If so, it is possible to infer lower limits to the bolometric luminosity and energetics of such a blackbody component. These limits, which are independent of the emissivity time dependence, are tighter for the very early data and correspond to energetics $\sim 10^{51}$ erg, too large to be produced by the breakout of a supernova shock. A further problem with the above interpretation concerns the luminosity of the observed X-ray blackbody component. It should be produced, in the shock breakout interpretation, as blackbody emission of approximately constant temperature from a surface area only slowly increasing with time. Although it has been suggested that, assuming anisotropy, the long duration of the X-ray blackbody component is consistent with a supernova shock breakout, the nearly constant size of the emitting surface requires some fine tuning. These difficulties support an alternative interpretation, according to which the emission follows the late dissipation of the fireball bulk kinetic energy. This in turn requires a small value of the bulk Lorentz factor.

Key words: radiation mechanisms: non-thermal – radiation mechanisms: thermal – gamma-rays: bursts.

1 INTRODUCTION

The observations of GRB 060218 by the *Swift* satellite (Gehrels et al. 2004) have prompted Campana et al. (2006, hereafter C06) to interpret the presence of a thermal, blackbody component in the soft X-ray band as the signature of the shock breakout of the associated supernova (SN) 2006aj (e.g. Mazzali et al. 2006; Modjaz et al. 2006). The low redshift ($z = 0.033$, Mirabal et al. 2006), together with an unusually long prompt emission of GRB 060218, allowed unprecedented coverage by all three of the *Swift* instruments (UVOT, XRT and BAT), providing simultaneous data from the optical to the soft gamma-ray range. In the optical–ultraviolet band, the data in the different UVOT/*Swift* filters showed a hard spectrum, which can be made consistent with a Rayleigh–Jeans $F(\nu) \propto \nu^2$ law by invoking a Small Magellanic Cloud (SMC) extinction law for the host absorption with $E(B - V) = 0.2$ plus a Galactic $E(B - V) = 0.14$ (C06). In the 0.2–10 keV energy range the prompt spectrum can be fitted by the sum of a $kT \sim 0.1$–0.2 keV blackbody plus a cut-off power law, also consistent with the BAT 15–150 keV data. A fit of the combined XRT and BAT spectrum (0.2–150 keV), integrated over ∼3000 s, returns a peak energy $E_{\rm peak} \sim 5$ keV, for which GRB 060218 is consistent with the relation between the time-integrated bolometric isotropic energy $E_{\rm iso}$ and the peak energy $E_{\rm peak}$ (Amati et al. 2002, 2007). GRB 060218 was underluminous, with $E_{\rm iso}$ slightly less than 10^{50} erg, and in this respect it resembles GRB 980425 (associated with SN 1998bw; Galama et al. 1998),[1] GRB 031203 (associated with SN 2003lw; Malesani et al. 2004) and GRB 030329 (associated with SN 2003dh; Stanek et al. 2003). From the temporal point of view, the time lag between hard and soft emission is consistent (Liang et al. 2006) with the lag–luminosity relation (Norris, Marani & Bonnel 2000).

Two peaks are clearly observed in the optical–ultraviolet light curve of GRB 060218: an initial flux increase lasting 3×10^4 s is followed by a fast decay until $t \sim 1.5 \times 10^5$ s after the trigger; a second peak at ∼10 d shows the typical spectral signatures of the underlying SN (Ferrero et al. 2006; Mirabal et al. 2006; Modjaz et al. 2006; Sollerman et al. 2006). Spectroscopic observations indicated a time-dependent expansion velocity: 2×10^4 km s^{-1} at day 3, $\sim 1.8 \times 10^4$ km s^{-1} at day 10 and a more rapid deceleration between days 10 and 15 after explosion (see fig. 2 in Pian et al. 2006). Polarization was detected a few days after trigger (Gorosabel et al. 2006) at a level of a few per cent, indicating some asymmetry of the emitting zone.

In the radio band, the flux between 2 and 22 d showed a typical power-law decay ($\propto t^{-0.8}$, Soderberg et al. 2006).

The X-ray (0.3–10 keV) light curve presented a smooth long-lasting (∼3000 s) peak followed by a fast decay. At 10^4 s the flux began a shallower decreasing phase ($\propto t^{-1.2}$) lasting several days.

[1]Note, however, that SN 2006aj is one order of magnitude weaker than SN 1998bw (Mazzali et al. 2006; Pian et al. 2006).

⋆E-mail: gabriele.ghisellini@brera.inaf.it

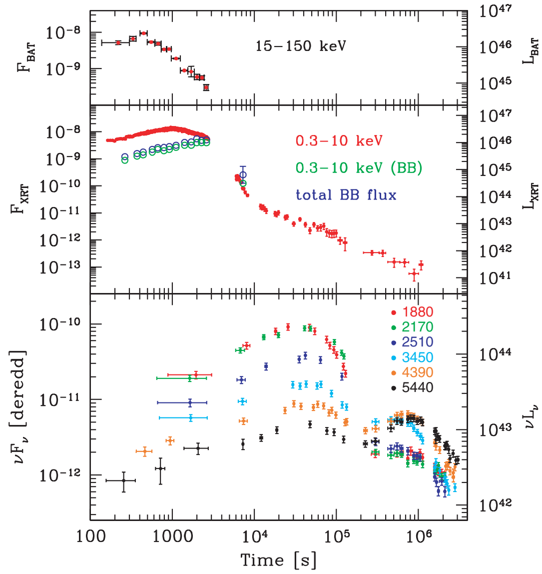

Figure 1. Top panel: light curve of the BAT 15–150 KeV flux of GRB 060218. Middle panel: light curves of the total (0.3–10 keV) X-ray flux of GRB 060218 (small red dots), the blackbody flux in the same energy range (green dots) and the bolometric flux of the blackbody component (blue dots). Data are from C06 and W07. Bottom panel: the light curve in the three UVOT/*Swift* optical–ultraviolet filters, de-reddened assuming a Galactic extinction $E(B-V)=0.14$ plus a host galaxy extinction $E(B-V)=0.2$ (for a Small Magellanic Cloud extinction curve for the latter). We adopt cgs units for all quantities.

The spectrum of such a phase is very soft, corresponding to an energy spectral index $\alpha\sim 2.3$ (Cusumano et al. 2006).

The complex behaviour of GRB 060218 is summarized in Fig. 1, which reports the available information on the light curves detected by all three of the *Swift* instruments. The top panel shows the light curve in the 15–150 keV band, as detected by BAT and analysed by Toma et al. (2007). The middle panel represents the 0.3–10 keV light curve as detected by XRT, and, separately, the light curve corresponding to the blackbody component only [as shown by C06 and Waxman, Mcszaros & Campana (2007, hereafter W07) too]. The time-dependent flux corresponding to the bolometric blackbody component is also plotted to show that its behaviour reproduces that of the 0.3–10 keV blackbody light curve. Note that the blackbody flux slightly increases with time until $t\sim 3000$ s, and that at 7000 s the absolute blackbody flux has decreased but its relative contribution to the total flux has increased. The bottom panel reports the light curve in the optical–ultraviolet filters of UVOT. Note that in C06 and in W07 no absorption correction has been applied and the light curves refer to specific fluxes multiplied by the FWHM of the different UVOT filters [$F=F(\lambda)\Delta\lambda$]. Here we have converted F into the quantity $\nu F_\nu[\nu F_\nu=\lambda F(\lambda)]$, and de-reddened the fluxes adopting, following C06, $E(B-V)=0.14$ (Galactic) plus $E(B-V)=0.2$ (host, with a SMC extinction law).

C06 interpreted the thermal X-ray spectral component, evolving towards lower temperatures and shifting into the optical–ultraviolet band, as emission following the breakout of a shock, driven by a mildly relativistic shell, into the dense wind surrounding the progenitor. Li (2007) modelled numerically the corresponding transient emission specifically for Type Ibc SNe produced by the core-collapse of Wolf–Rayet (WR) stars surrounded by dense winds. However, for the case of GRB 060218/SN 2006aj such a model required an unrealistically large core radius of a WR progenitor star (but see W07).

The interpretation of the observational properties of GRB 060218 therefore appeared puzzling. Ghisellini, Ghirlanda & Tavecchio (2007, hereafter Paper I) discussed the alternative possibility that the optical-to-X-ray radiation is non-thermal emission produced in a fireball moving with a moderate bulk Lorentz factor ($\Gamma\sim 5$), and the thermal X-ray component is due to some dissipation occurring within the jet (possibly just below its photosphere).

Recently, W07 fiercely argued against alternative interpretations by presenting the details of the shock breakout hypothesis in an anisotropic SN explosion. According to W07, the anisotropy of the explosion easily accounts for the long-lasting X-ray thermal emission.

In this Letter we re-examine some aspects of the scenario proposed by W07. In particular, following their interpretation, for both the optical and the X-ray blackbody components, we derive consequences which we see as its major problems, so severe as to require alternative explanations. In Section 2 we point out that, if the optical–ultraviolet emission belongs to a blackbody component, the evolution of the energy and temperature of the blackbody, as inferred from the available *Swift*/UVOT optical observations, implies energetics for the early phases that are too large.

We then show (Section 3) that the rather slow increase of the surface emitting the X-ray blackbody is not a natural consequence of the anisotropic shock breakout scenario, but rather favours an alternative interpretation, where the emitting surface is associated with the transparency radius of a relatively long-lived, mildly relativistic ($\Gamma\sim$ a few) jet. Indeed, if the X-ray blackbody is produced following a funnel/jet shear instability [according to the ideas put forward by Thompson (2006) and Thompson, Meszaros & Rees (2007)], then the presence of the blackbody component requires a small value of Γ, of the order of $1/\theta_j$, where θ_j is the jet opening angle.

2 BLACKBODY OPTICAL EMISSION?

We assume that the optical–ultraviolet emission up to 10^5 s corresponds to the Rayleigh–Jeans part of a blackbody component, as suggested by C06 and W07. For any assumed expansion law, it is then possible to estimate the time dependence of the emitting surface. Also the optical–ultraviolet observations constrain the temperature dependence on time. Thus it is possible to infer the bolometric luminosity and energetics.

Consider the surface emitting as a blackbody expanding with a velocity v, starting from an initial radius R_0. In general, the expansion velocity of the photosphere will decrease with time. The model adopted by W07 postulates that the photospheric radius expands as $R\propto t^{4/5}$, at least for $R>R_0$. Adopting the same dependence, equation (18) in W07 can be re-written as

$$R = R_0 + 3.6\times 10^{10} t^{4/5}\ \mathrm{cm}. \quad (1)$$

This implies a photospheric expansion speed $v\propto t^{-1/5}$, corresponding to the observed velocities (derived from spectral modelling) 2–3 d after the explosion [i.e. equation (1) gives $v=2.38\times 10^4$ km s^{-1} after 3 d, in agreement with the measurements reported by Pian et al. (2006)].

We then assume that for $t<1.2\times 10^5$ s the optical–ultraviolet spectrum corresponds to the Rayleigh–Jeans part of a blackbody spectrum:

$$\nu F_\nu = 2\pi^2 kT\left(\frac{R}{d}\right)^2\frac{\nu^3}{c^2}, \quad (2)$$

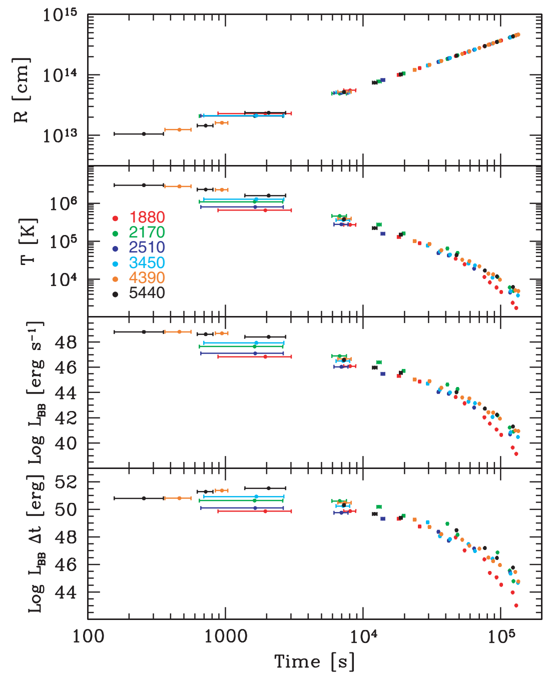

Figure 2. From top to bottom: radius of the blackbody emitting surface, $R = R_0 + 3.6 \times 10^{10} t^{4/5}$ with $R_0 = 7.5 \times 10^{12}$ cm, as suggested by W07; temperature of the blackbody derived by assuming that the whole spectrum belongs to the Rayleigh–Jeans part of the blackbody component; the corresponding blackbody bolometric luminosity; the blackbody energetics, estimated as $E_{\rm BB} = \Delta t L_{\rm BB}$, where Δt is the exposure time of each flux measurement. Different colours refer to observations in different filters.

where the distance $d = 145$ Mpc. This in turn defines the temporal dependence of the blackbody temperature:

$$T = \frac{\nu F_\nu}{2\pi^2 k} \left(\frac{d}{R}\right)^2 \frac{c^2}{\nu^3}. \tag{3}$$

As the temperature decreases with time, the assumption that the emission is in the Rayleigh–Jeans regime of the blackbody spectrum is appropriate, especially for the early data which set the most severe constraints on the total energetics. Within W07's scenario, the blackbody peak is entering the UVOT band at $t \sim 10^5$ s, and this implies that the temperature estimated at 1880 Å is slightly less than that estimated at all other wavelengths (see Fig. 2).

Fig. 2 summarizes our results, showing (from top to bottom) the time profiles of the assumed blackbody radius (i.e. equation 1), temperature and bolometric blackbody luminosity. In the bottom panel is also reported an estimate of the blackbody energetics, obtained by multiplying the luminosity by the exposure time Δt corresponding to each flux measurement. The quantity $E_{\rm BB} = L_{\rm BB}\Delta t$ thus provides a 'proxy' of the implied blackbody energetics.

The implied blackbody luminosities are very large in the early phases, being of the order of 10^{48}–10^{49} erg s^{-1}, implying blackbody energetics of $\sim 10^{51}$ erg (bottom panel). This is comparable to the entire kinetic energy of SN2006aj, estimated to be $\sim 2 \times 10^{51}$ erg by Mazzali et al. (2006).

We have considered different expansion laws, clearly bound by the condition $v < c$, and other (reasonable) values for R_0. The result does not change: at early times, i.e. for the smallest photospheric radii, the observed flux requires high temperatures, and thus large blackbody luminosities.

The resulting energetics are too large to originate as blackbody emission from the heated SN envelope. Therefore the observed flux is not blackbody radiation, although it might correspond to the absorbed (Rayleigh–Jeans) portion of a spectrum becoming transparent below the shortest observed wavelengths. Note that the $F(\nu) \propto \nu^2$ dependence somehow relies on the assumed host extinction: less extinction implies a softer slope. Indeed, Sollerman et al. (2006) argued for values $E(B-V)_{\rm Gal} = 0.127$ and $E(B-V)_{\rm host} = 0.042$, significantly smaller than those adopted by C06 [who required that the de-reddened optical–ultraviolet data follow a $F(\nu) \propto \nu^2$ law]. Assuming the $E(B-V)$ proposed by Sollerman et al. (2006), we showed (in Paper I) that the optical–ultraviolet emission can still be part of a synchrotron spectrum, partially self-absorbed, connecting the optical–ultraviolet to the non-thermal X-ray flux. Alternatively, the optical–ultraviolet and X-ray fluxes could belong to two unrelated components: in this case the optical–ultraviolet and X-ray spectra should cut off below 1880 Å and $\sim$0.3 keV, respectively. Both interpretations minimize the required energetics.

3 THE LONG-LASTING X-RAY BLACKBODY

The fluxes corresponding to the X-ray blackbody component reported in C06 and W07 increase until $t \sim 3000$ s. Such a component, albeit fainter, is still detected at about $t \sim 7000$ s. In Fig. 1 we report the X-ray light curve as presented in C06 and W07 together with the light curve inferred for the bolometric blackbody flux to show that they follow the same trend, namely $F_{\rm BB} \propto t^{2/3}$. The radius R of the (projected) emitting surface can be derived directly from the fitting of the X-ray data, since the temperature of the X-ray blackbody is determined and the distance of GRB 060218 is known. The temporal behaviour of R scales approximately as $R \sim a + bt \sim 5 \times 10^{11} + 3 \times 10^8 t$ cm (see fig. 3 in C06), giving a rather modest expansion velocity, $v \sim 3 \times 10^8$ cm s^{-1} $\sim 0.01\,c$. As the projected emitting surface scales as

$$S_{\rm obs}(t) = 4\pi(a+bt)^2, \tag{4}$$

the temporal dependence of the blackbody temperature follows $T \propto t^{1/6}/(5 \times 10^{11} + 3 \times 10^8\, t)^{1/2} \approx$ constant.

As mentioned, the puzzling properties of the X-ray blackbody component, if interpreted as produced by the SN shock breakout, are: (i) the long duration; (ii) the large luminosity and energetics; and (iii) the slowly increasing emitting surface. Li (2007) numerically examined the relevant characteristics of shock breakouts in WR stars with strong winds, finding that although the presence of the wind allows the shock to radiate more efficiently, the resulting luminosities are still insufficient to account for that observed from GRB 060218. Also the predicted total duration of the event ($\sim$35 s) is much shorter than observed ($\sim$3000–7000 s): indeed it is argued that possible anisotropies – although they can partially increase the power generated – cannot change the duration.

W07 instead claimed that the wind opacity, by leading to a photospheric radius significantly exceeding the stellar radius, is the key ingredient to explain the large luminosity. Furthermore, they stated that the long event duration is evidence for anisotropy, the origin of which, however, is different from that considered by Li (2007). According to W07, because of the asymmetry the SN shock surface reaches transparency at different times, depending on the direction, thus accounting for the long-lasting emission. Since the blackbody luminosity increases with time, in this scenario the shock should radiate more sideways than along the polar axis. Although this interpretation is certainly possible, its realization requires some fine-tuning, as illustrated by the following simple example.

Assume for simplicity that the anisotropy concerns only the dependence of the shock velocity on the angle θ from the polar axis, and that the whole emitting surface reaches transparency at the same radius R from the stellar centre. The projected area at time t is given by

$$dS_{\perp} = 2\pi R^2 \sin\theta \cos\theta \, d\theta = -2\pi R^2 \mu \frac{d\mu}{dt} \, dt. \tag{5}$$

The time derivative of equation (4) leads to

$$8\pi b(a + bt) = -2\pi R^2 \mu \frac{d\mu}{dt}, \tag{6}$$

the solution of which for θ is

$$\sin^2\theta = \frac{4b^2}{R^2} t^2 + \frac{8ab}{R^2} t \rightarrow t = \frac{a}{b} \left[\left(1 + \frac{R^2}{4a^2} \sin^2\theta \right)^{1/2} - 1 \right]. \tag{7}$$

For $a = 5 \times 10^{11}$ cm and $b = 3 \times 10^8$ cm s^{-1} the condition $\sin\theta < 1$ at 7000 s implies that $R > 5.1 \times 10^{12}$ cm. Since the blackbody emission lasts much longer than the characteristic light crossing time R/c, light traveltime effects can be neglected. Thus the elapsed time t since the beginning of the blackbody emission is

$$t = R \left[\frac{1}{v(\theta)} - \frac{1}{v_0} \right] \rightarrow v(\theta) = \frac{v_0}{1 + v_0 t/R}, \tag{8}$$

where $v_0 \equiv v(\theta = 0)$. Substituting equation (7) into equation (8) results in an almost constant velocity at small angles, decreasing as $1/\sin^2\theta$ for larger θ.

Different velocity profiles (or a dependence of the transparency radius on θ) would produce a different behaviour of the measured emitting surface. Also, the observed increase of the blackbody luminosity with time requires a specific profile in θ for the energy released by the shock.

We propose that the near-constancy of the blackbody emitting surface supports an alternative scenario, in which most of the emission is produced at the transparency radius of a 'gamma-ray burst' ('GRB') jet. Models along these lines have already been proposed by Thompson (2006) and Thompson et al. (2007) in a different context: they suggest that the blackbody component originates following shear instabilities between the jet and the funnel of the progenitor star and is of course released when the fireball becomes transparent. According to Daigne & Mochkovitch (2002) this occurs at a radius

$$R_{\rm ph} \sim 4.6 \times 10^{12} \frac{L_{\rm k,48}}{(\Gamma/4)^3} \text{ cm}, \tag{9}$$

where $L_{\rm k} = 10^{48} L_{\rm k,48}$ erg s^{-1} is the fireball kinetic power. The relevant radius for the blackbody emission is then min $[\theta_{\rm j}, 1/\Gamma]R_{\rm ph}$, which is comparable to the radii inferred from observations if the jet is not highly collimated and/or the bulk Lorentz factor is small. The resulting isotropic blackbody luminosity

$$L_{\rm BB,iso} \sim 4\pi \frac{R^2_{\rm ph}}{\Gamma^2} \sigma T^4 \sim 1.5 \times 10^{46} \frac{L^2_{\rm k,48}}{(\Gamma/4)^8} \left(\frac{T}{2 \times 10^6} \right)^4 \text{ erg s}^{-1} \tag{10}$$

accounts for the observed one.

Following these lines, in Paper I we estimated the energy requirements posed by assuming that either the blackbody represents the 'fossil' radiation that accelerated the fireball in the first place, or it is produced at larger radii, following some dissipation event. The latter option was clearly favoured: indeed in this case the photon energies do not degrade significantly owing to expansion between the dissipation and the transparency radii, lowering the required energetics.

One possible origin of late dissipation is the process quoted above, proposed by Thompson (2006) and Thompson et al. (2007), namely shear instability between the fireball and the stellar funnel. The resulting energy peak of the blackbody spectrum was then associated with the peak of the (time integrated) spectrum of the prompt emission, and this allowed them to account for the $E_{\rm peak}$–$E_{\rm iso}$ relation in terms of blackbody emission. Note that GRB 060218 obeys the Amati relation, but only if the peak energy of the overall X-ray spectrum is considered (i.e. not the blackbody peak energy)

Recently, by analysing the sample of GRBs observed both by BATSE on board *CGRO* and by the Wide Field Camera on board *BeppoSAX*, Ghirlanda et al. (2007) found that the presence of a dominating blackbody component faces severe problems. Note that all of the GRBs considered follow the Amati relation. Therefore the fireball/funnel instability, if it occurs, may not be responsible for the peak of the prompt spectrum, i.e. the bulk of the emission. We clearly cannot exclude that it is responsible for blackbody emission with lower temperature and luminosity, as observed in GRB 060218.

In all of the scenarios proposed to explain the peculiar properties of GRB 060218, a bulk Lorentz factor of the order of unity is assumed, i.e. a factor of $\sim$100 smaller than the 'canonical' value. The detection of the X-ray blackbody might thus be associated with a small Γ factor. Indeed, a key point in the scenario by Thompson et al. (2007) concerns the value of Γ required for efficient dissipation: this has to be of the order of $\sim 1/\theta_{\rm j}$. This may be the clue to understand why blackbody emission has been detected only in the spectrum of GRB 060218: for small-Γ fireballs the shear instability may be efficient enough to reveal itself through the presence of a blackbody component, while for GRB fireballs with $\Gamma \gg 1/\theta_{\rm j}$ this should not be detectable.

GRB 980425 is another event possibly characterized by a small-Γ fireball. Thus it is a likely candidate to show observable blackbody emission in soft X-rays,[2] although it would have been impossible to reveal it with the detectors in 1998.

4 SUMMARY AND CONCLUSIONS

We have re-examined the possibility that the thermal components detected in the early phases of the optical and X-ray emission of GRB 060218 are due to the shock breakout of the associated SN 2006aj.

We have found that if the optical–ultraviolet radiation corresponds to the Rayleigh–Jeans part of a blackbody spectrum, the data imply very large blackbody luminosities, especially at early times (i.e. the first few thousand seconds after the trigger). The derived values cannot be accounted for as emission by material in the envelope/wind of the star heated by the shock crossing.

Instead, the proposed interpretation that the optical–ultraviolet–X-ray spectrum originates as non-thermal synchrotron emission appears tenable and has two major advantages: (i) the optical–ultraviolet spectrum can be softer than ν^2 [allowing a smaller optical extinction, as indicated by Sollerman et al. (2006)], and (ii) the energy requirement is significantly reduced with respect to the shock breakout scenario.

The blackbody spectrum detected in the X-ray band constrains the emitting surface to depend only weakly on time. The long total

[2] The possibility that the prompt spectrum of GRB 980425 could have been similar to that of GRB 060218 has been discussed by Ghisellini et al. (2006).

duration, which greatly exceeds the light crossing time, led W07 to propose that the persistence of the blackbody component is due to anisotropy, namely the fact that transparency is reached at different times by different parts of the shock surface, because either the shock velocity or the photospheric radius is a function of the polar angle. Although this is a viable possibility, we have pointed out that only a specific dependence on the polar angle gives rise to the observed behaviour: in general, anisotropy implies that the resulting observed (projected) surface changes with time.

Instead, the almost constant X-ray-emitting surface supports a scenario in which the X-ray blackbody emission is produced inside a jet, before transparency is reached. The transparency radius corresponds to that inferred from observations if the bulk Lorentz factor is small, of the order of a few. This is also the condition to develop efficient shear instability modes between the jet and the funnel, and explains why the X-ray blackbody component can be rarely observable (i.e. only when the bulk Lorentz factor is of the order of the inverse of the jet opening angle).

We noted that GRB 060218 obeys the $E_{\rm peak}$–$E_{\rm iso}$ relation only if the entire (non-thermal?) X-ray and gamma-ray emission component, which peaks at $\sim$5 keV, is considered (the X-ray thermal emission peaks at too low energies). If this is not a coincidence, it implies that the physical process underlying the Amati relation is robust and independent of the bulk Lorentz factor. Similar considerations hold for the lag–luminosity relation, which GRB 060218 obeys as well.

The bottom line of this re-analysis is that we are still puzzled about the self-consistency of the SN shock breakout interpretation of the optical, ultraviolet and thermal X-ray emission of GRB 060218.

On the other hand, this burst *is* associated with SN 2006aj, and therefore some signs of the associated shock breakout should be present. Why do we not observe it? The simplest answer is that the emission associated with the shock break out is weaker than other spectral components.

ACKNOWLEDGMENTS

This work has been partially funded by a 2005 INAF grant. We thank the anonymous referee for useful criticism. We are grateful to Annalisa Celotti for comments and discussion.

REFERENCES

Amati L. et al., 2002, A&A, 390, 81
Amati L., Della Valle M., Frontera F., Malesani D., Guidorzi C., Montanari E., Pian E., 2007, A&A, 463, 913
Campana S. et al., 2006, Nat, 442, 1008 (C06)
Cusumano G., Moretti A., Tagliaferri G., Kennea J., Burrows D., 2006, GCN Circ. 4786
Daigne F., Mochkovitch R., 2002, MNRAS, 336, 1271
Ferrero P. et al., 2006, A&A, 457, 857
Galama T. et al., 1998, Nat, 395, 670
Gehrels N. et al., 2004, ApJ, 611, 1005
Ghirlanda G., Bosnjak Z., Ghisellini G., Tavecchio F., Firmani C., 2007, MNRAS, 379, 73
Ghisellini G., Ghirlanda G., Mereghetti S., Bosnjak Z., Tavecchio F., Firmani C., 2006, MNRAS, 372, 1699
Ghisellini G., Ghirlanda G., Tavecchio F., 2007, MNRAS, 375, L36 (Paper I)
Gorosabel J. et al., 2006, A&A, 495, L33
Li L.-X., 2007, MNRAS, 375, 240
Liang E., Zhang B., Zhang B., Dai Q. G., Norris J., Stamatikos M., Gehrels N., 2006, ApJ, 653, L81
Malesani D. et al., 2004, ApJ, 609, L5
Mazzali P., Deng J., Nomoto K., Pian E., Tominaga N., Tanaka M., Maeda K., 2006, Nat, 442, 1018
Mirabal N., Halpern J. P., An D., Thorstensen J. R., Terndrup D. M., 2006, ApJ, 643, L99
Modjaz M. et al., 2006, ApJ, 645, L21
Norris J. P., Marani G. F., Bonnel J. T., 2000, ApJ, 534, 248
Pian E. et al., 2006, Nat, 442, 1011
Soderberg A. M. et al., 2006, Nat, 442, 1014
Sollerman J. et al., 2006, A&A, 454, 503
Stanek K. Z. et al., 2003, ApJ, 591, L17
Thompson C., 2006, ApJ, 651, 333
Thompson C., Meszaros P., Rees M. J., 2007, ApJ, 666, 1012
Toma K., Ioka K., Sakamoto T., Nakamura N., 2007, ApJ, 659, 1420
Waxman E., Mészáros P., Campana S., 2007, ApJ, 667, 351 (W07)

This paper has been typeset from a TEX/LATEX file prepared by the author.