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Puzzled by GRB 060218

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ABSTRACT

We study the optical–UV/X-ray spectral energy distribution of GRB 060218 during the prompt and what seems to be the afterglow phases. The results are puzzling, since if the optical–UV and the X-ray emission belong to a single blackbody then its luminosity is too large, and this blackbody cannot be interpreted as the signature of the shock breakout of the supernova. There are also serious problems in associating the emission expected from the supernova shock breakout with either the optical–UV or the X-ray emission. In the former case we derive too small ejecta velocities; in the latter case, in contrast, the required velocity is too large, corresponding to the large radius of a blackbody required to peak close to the UV band. We then present what we think is the most conservative alternative explanation, namely a synchrotron spectrum, self-absorbed in the optical–UV and extending up to the X-ray band, where we observe the emission of the most energetic electrons, which are responsible for the exponential roll-over of the spectrum. The obtained fit can explain the entire spectrum except the blackbody observed in the X-rays, which must be a separate component. The puzzling feature of this interpretation is that the same model is required to explain the spectrum also at later times, up to 10^5 s, because the optical–UV emission remains constant in shape and also (approximately) in normalization. In this case the observed X-ray flux is produced by self-Compton emission. Thus the prompt emission phase should last for $\sim 10^5$ s or more. Finally, we show that the blackbody observed in X-rays, up to 7000 s, can be photospheric emission from the cocoon or stellar material, energized by the gamma-ray burst jet at radii comparable to the stellar radius (i.e. 10^{10}–10^{11} cm), not very far from where this material becomes transparent (e.g. 10^{12} cm).

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

1 INTRODUCTION

The gamma-ray burst (GRB) that exploded on 2006 February 18 is a low-redshift burst ($z = 0.033$, Mirabal et al. 2006), associated with the Type Ibc supernova SN 2006aj (e.g. Modjaz et al. 2006; Mazzali et al. 2006). Due to its long duration (more than 3000 s), GRB 060218 could be followed simultaneously with the BAT, XRT and UVOT instruments on board the *Swift* satellite (Gehrels et al. 2004). The 0.3–10 keV X-ray light curve (followed by XRT starting 157 s after the BAT trigger) presents three main phases (Campana et al. 2006, hereafter C06): phase X1 – a smooth/long ($\sim 3 \times 10^3$ s) bump peaking at $\sim 10^3$ s whose time-integrated spectrum shows a non-thermal component (power law with an exponential cut-off) peaking (in νF_ν) in the X-ray band ($E_{\rm peak} \sim 5$ keV) and a blackbody which comprises about 20 per cent of the total 0.3–10 keV flux and dominates the soft X-ray energy band ($kT \sim 0.13$ keV); X2 – a steep power-law (or exponential) time-decay up to 10^4 s still showing a slightly softer ($kT \sim 0.1$ keV) blackbody component (comprising about 50 per cent of the total flux) together with a softer non-thermal component; and X3 – a shallower flux decay ($\propto t^{-1.2}$) starting at 10^4 s, and lasting up to several days, with a very soft (energy spectral index $\alpha \sim 2.3$; Cusumano et al. 2006) non-thermal component. The optical–UV light curve presents two phases: in phase UV1 there is a slow increase of the flux, peaking at $\sim 8 \times 10^4$ s, followed by a fast decay up to $\sim 1.5 \times 10^5$ s; in phase UV2 there is a second bump peaking at ~ 10 d showing the typical spectral signatures of the underlying supernova (Ferrero et al. 2006; Mirabal et al. 2006; Modjaz et al. 2006; Sollerman et al. 2006) and suggesting photospheric expansion velocities of 2×10^4 km s^{-1} (e.g. Pian et al. 2006). Finally, in the radio band, the flux between 2 and 22 d shows a typical power-law decay ($\propto t^{-0.8}$, Soderberg et al. 2006).

Despite the wealth of available information, some of the observed properties of GRB 060218 are not yet understood. In fact, although the radio flux could be due to external shocks, the radio spectrum at

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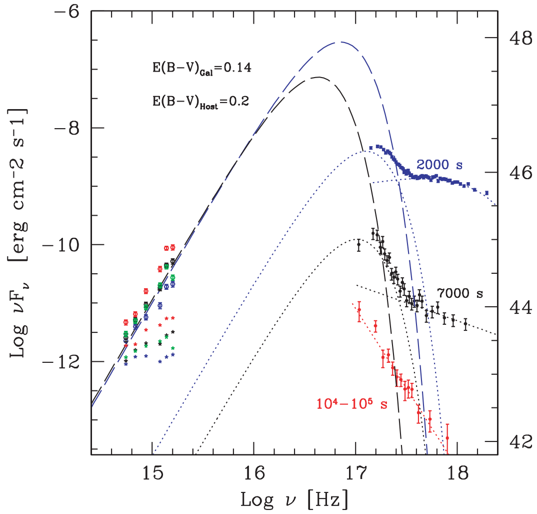

Figure 1. The SED of GRB 060218 at different times. Blue: 2000 s (integrated for ∼400 s for the X-ray); black: 7000 s (integrated for ∼2500 s); red: 40 000 s; green: 1.2×10^5 s (only UVOT data are shown). The optical–UV data are taken from C06 while the X-ray data have been re-analysed by us. The optical–UV data lie above the blackbody found by fitting the X-ray data (dotted lines). Instead, the optical–UV data seem to identify another blackbody component (long-dashed lines) which is inconsistent with the X-ray data at the same epochs. Small crosses without error bars are UVOT data not de-absorbed. De-absorbed data [with a galactic $E(B-V) = 0.14$ plus a host $E(B-V) = 0.2$] are shown with error bars.

5 d is inconsistent with the strong X-ray emission at the same epoch (Soderberg et al. 2006). Moreover, the typical late-time X-ray light curve decay (phase X3) is hardly reconcilable with the extremely soft spectrum in the framework of the external shock model for GRB afterglows. This suggests that the late-time X-ray emission might be produced by continued activity of the central engine (i.e. 'central engine afterglow' – Fan, Piran & Xu 2006).

2 THE SPECTRAL ENERGY DISTRIBUTION OF GRB 060218

The most striking characteristic of GRB 060218 is perhaps the observation, in the XRT 0.2–10 keV band, of a quasi-steady blackbody component at a temperature of ∼0.18–0.1 keV, observed up to 7000 s (i.e. phases X1 and X2) and with a total energy of $\sim 10^{49}$ erg. At optical–UV frequencies as well, the emission is well described by the Rayleigh–Jeans tail of a blackbody spectrum up to 10^5 s after trigger (phase UV1). It has been proposed (C06) that the optical–UV (UV1) *and* the X-ray (X1 and X2) emission are produced by the same process: the shock breakout of the supernova.

In Fig. 1 we show the optical[1] to X-ray spectral energy distribution (SED) of GRB 060218 roughly corresponding to the same three epochs (X1, X2 and X3) as described in the introduction. Both the UVOT and the XRT data have been de-absorbed, using the same $N_{\rm H}$ and $E(B-V)$ values as given in C06. However, one can see that the optical–UV data, independently of the assumed extinction, are above the extrapolation of the blackbody emission observed in XRT. Furthermore, the optical–UV data de-reddened using the values in C06 describe, at early times, a Rayleigh–Jeans tail of a blackbody.

If the X-ray emission and the optical–UV flux belong to the same blackbody component, then the derived blackbody luminosity is huge, exceeding 10^{48} erg s^{-1}. This luminosity, if produced by the subrelativistic supernova shock breakout, should not be boosted by relativistic effects. Since this luminosity would last for $\sim 10^4$ s, we would then infer a total radiated energy exceeding 10^{52} erg. This energy is close to (or above) the total kinetic energy of the supernova ejecta $E_{\rm K,SN} \sim 2 \times 10^{51}$ erg (Mazzali et al. 2006). Furthermore, trying to model the X-ray data with a cut-off power law plus a blackbody equal to the one joining the optical–UV and the X-rays (long-dashed lines in Fig. 1) produces an unacceptable fit. We therefore consider this possibility as highly unlikely.

Consider now the case of a multi-colour blackbody, joining the optical–UV and X-ray bands. In this case the optical–UV emission, belonging to the Rayleigh–Jeans tail of the coldest blackbody, is characterized by a very large radius (of the order of 10^{15} cm). This radius cannot correspond to the radius at which the supernova ejecta have arrived after 2000 s from the trigger, if we maintain the hypothesis that the supernova and the GRB exploded nearly simultaneously (Mirabal et al. 2006).

The total energetics of a blackbody joining the optical–UV and X-ray data are so large as to be problematic even if it is beamed radiation produced by a relativistically moving cocoon, since it would exceed by orders of magnitude the energetics produced by the jet which is supposed to energize it, and whose emission should be observed, if the burst is not misaligned.

3 X-RAY OR OPTICAL–UV BLACKBODY AS SUPERNOVA SHOCK BREAKOUT?

Since we have discarded the possibility of a single (or a multi-colour) blackbody joining the optical–UV and the X-ray emission, let us discuss the case of a supernova shock breakout associated with either the optical–UV emission or the X-ray blackbody.

Assume first that the association is with the X-ray blackbody. Detailed modelling of the shock breakout (Li 2006) flashes in supernova explosions predicts a temperature of 1.8 keV (0.2 keV), a duration of ∼20 s and an emission in the X-ray band amounting to a radiated energy of $\sim 10^{47}$ erg for a typical hypernova, and $\sim 10^{45}$ erg for 'normal' Type Ibc supernovae. These values are inconsistent with the temperature, duration and energetics of the observed X-ray blackbody component of GRB 060218. In addition to this, the radii derived from the blackbody fit to the X-ray data (C06) are increasing in time, but at a rate corresponding to a very small velocity: ∼3000 km s^{-1}, in contrast to the (decreasing) velocities derived by the optical spectroscopy by Pian et al. (2006), which shows velocities of 20 000 km s^{-1} at 1 d from the trigger.

Consider now the association with the optical–UV. In this case one can assume that the flux in this band belongs to a blackbody peaking at (or not too far above) the largest observed frequency (to limit the implied energetics), but in this case the corresponding blackbody radius is around 10^{15} cm. Then, if the supernova exploded around the same time as the GRB, the implied velocity of the ejecta exceeds *c*.

In summary: a single blackbody joining the optical–UV and the X-ray fluxes is too energetic; the blackbody emission expected from a supernova shock breakout cannot be associated with the blackbody observed in the X-rays (too small inferred velocities of the ejecta), or with a blackbody peaking in the UV (too large ejecta velocities).

[1] The optical–UV data shown in C06 are not de-absorbed, and are in the form of specific fluxes multiplied by the FWHM widths of the different UVOT filters [i.e. what is plotted is $F = F(\lambda)\Delta\lambda$]. To convert into νF_ν fluxes, we have used $\nu F_\nu = \lambda F(\lambda)$.

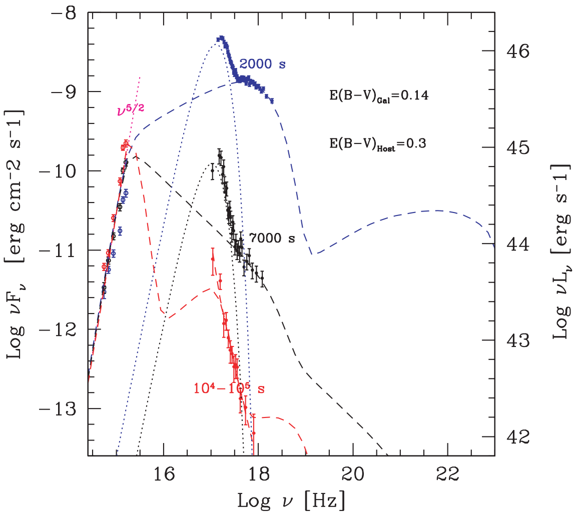

Figure 2. The SED of GRB 060218 at different times, as in Fig. 1, but with the optical–UV points de-reddened with $E(B-V)_{\rm host} = 0.3$ instead of 0.2. This produces an optical–UV spectrum $\propto \nu^{5/2}$. We also show the SSC model, discussed in the text, for the three SEDs for which we have simultaneous UVOT and XRT data (i.e. at 2000, 7000 and $\sim 10^4$–10^5 s after trigger).

We are then forced to explore alternative possibilities to explain the SED of this burst. One possibility is that the entire SED (except the X-ray blackbody component) is produced by the synchrotron process, which can account for the optical–UV very hard spectrum if it self-absorbs at or above the UV band. This model will be discussed in the next section.

4 A SYNCHROTRON SELF-COMPTON MODEL

Assume that the overall optical–UV to X-ray SED, excluding the X-ray blackbody, belongs to the same synchrotron spectrum. For simplicity assume that this radiation is produced in a jet, with cross-sectional radius R, width $\Delta R'$ (as measured in the comoving frame) and semi-aperture angle ψ, embedded in a tangled magnetic field B, moving with a bulk Lorentz factor Γ. We assume that the radiation we observe is produced at a fixed distance from the jet apex. In other words, the conversion of bulk kinetic into random energy occurs at the same location along the jet, for the entire duration of the burst. The viewing angle is supposed to be smaller than ψ. Assume also that the emitting particles are distributed in energy according to a simple power law $N(\gamma) = K\gamma^{-p}$ between $\gamma_{\rm min}$ and $\gamma_{\rm max}$. We require that the synchrotron spectrum self-absorbs at a frequency $\nu_{\rm a}$ close to 10^{15} Hz. If $\gamma_{\rm min}$ is small (around unity), then the self-absorbed spectrum should be $\propto \nu^{5/2}$. Note that the optical–UV spectrum shown in Fig. 1 *assumed* a spectral slope $\propto \nu^2$ to derive the extinction in the host frame (C06). A spectrum $\propto \nu^{5/2}$ requires a small increase in the host extinction: $E(B-V)_{\rm host}$ increases from 0.2 to 0.3.

This is shown in Fig. 2, together with the results of the synchrotron self-Compton model (dashed lines), at $\sim$2000 s, at $\sim$7000 s and at a time between 10^4 and 10^5 s.

For the 2000 s spectrum, we have used $R = 7 \times 10^{11}$ cm, $\Delta R' = 10^{11}$ cm, $\Gamma = 5$, a semi-aperture angle of the jet $\psi = 0.2$, $B = 3 \times 10^5$ G and $p = 2.3$, between $\gamma_{\rm min} = 1$ and $\gamma_{\rm max} = 360$. We assumed a Doppler factor $\delta \sim 2\Gamma$, appropriate for on-axis observers (but the results are nearly the same for observers within the jet opening angle). For the comoving intrinsic luminosity we set $L' = 6.5 \times 10^{42}$ erg s^{-1}. To obtain the isotropically equivalent luminosity we used $L = L'\,\delta^2/(1 - \cos\psi)$, while the monochromatic luminosities have been boosted by $L(\nu) = L'(\nu')\,\delta/(1 - \cos\psi)$. The self-Compton luminosity is a factor of $\sim$30 less than the synchrotron one.

For the 7000 s spectrum we can describe the spectrum by changing only the slope of the electron distribution from 2.3 to 4.2, and keeping all other parameters constant. The choice of p is not free, since it is dictated by the measured slope of the X-ray continuum. This 'drastic' change of p on such a short time-scale may appear odd, but it is not unprecedented: in fact blazars show such a behaviour quite often [see e.g. Mrk 501 in Sambruna et al. (2000)].

For the late SED (at 10^4–10^5 s), we again changed only the electron distribution function, introducing a break at $\gamma_{\rm break} = 7.4$. Below this break $p = 2$, above it $p = 15$, a value so large as to mimic an exponential roll-off. The observed radiation in the X-rays corresponds to the first-order self-Compton scattering. Within this scheme, since the optical–UV flux remains almost the same, and is described by an absorbed spectrum, we have that $R^2\,B^{-1/2}$ must be the same as before. Therefore this radiation *is not afterglow, but late prompt emission* [as also proposed by Fan et al. (2006)]. Since the slope of the electron distribution is much steeper, what we see in the X-rays at such late times is the first-order self-Compton spectrum. This explains why we observe an uncommonly soft X-ray spectrum at times $>10^4$ s.

Using the chosen parameters, the value of the corresponding Poynting flux $L_B = \pi R^2\Gamma^2 c B^2/(8\pi) = 4 \times 10^{45}$ erg s^{-1}. If this corresponds to a conserved quantity, then the value of B at a distance of 5×10^5 cm (where $R = 10^5$ cm) from the central power-house is $B_0 = 2 \times 10^{12}$ G. The value of L_B is much greater than the kinetic power carried by the protons associated with the emitting electrons (assuming one proton per electron), but there is the possibility that only a fraction of leptons are accelerated. In this case the kinetic energy of protons would increase.

The self-absorbed synchrotron luminosity $L'(\nu')/\nu'^{5/2} \propto R^2B^{-1/2}$, while for the optically thin part $L'(\nu')\nu'^{\alpha} \propto R^2\Delta R' K B^{1+\alpha}$ where $\alpha = (p-1)/2$ is the energy spectral index. Including δ, we then have five unknowns (δ, R, $\Delta R'$, B, K) and only two observables (the optically thick and thin parts of the spectrum). The cut-off energy fixes $\gamma_{\rm max}$ directly once B and δ are given, and the observed slope fixes p directly.

The solution found therefore is not unique, but we were guided in the choice of the parameters by some additional constraints. (i) The Comptonization $y \sim \sigma_{\rm T} K\,\Delta R'\langle\gamma^2\rangle$ parameter should not be greater than unity, so as not to produce too much self-Compton emission. (ii) The required self-absorption frequency is rather large, and needs a large value of the magnetic field, suggesting a small size of the source. However, a lower limit to the size of the emission region can be obtained by requiring that it is transparent to Thomson scattering. (iii) In strong magnetic fields, the radiative cooling times are much shorter than the dynamical times, and all electrons can cool down to $\gamma_{\rm min} = 1$. These additional constraints, however, are not enough to single out a unique solution, and the models shown in Fig. 2 should be considered as illustrative examples only. This synchrotron self-Compton model, on the other hand, can explain in a simple way why the optical UV flux changes much less than the X-ray flux, since it is due to the self-absorbed flux, which is much less sensitive to changes in the electron distribution.

Another concern is the adopted value of the optical extinction, which is uncertain. Sollerman et al. (2006) proposed a significantly lower value: $E(B-V)_{\rm Gal} = 0.127$ and $E(B-V)_{\rm host} = 0.042$.

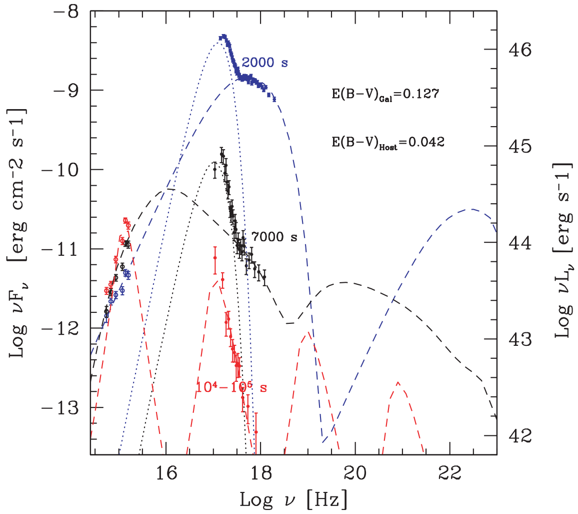

Figure 3. As in Fig. 2, but with the optical–UV points de-reddened with $E(B-V)_{\rm Gal} = 0.127$ and $E(B-V)_{\rm host} = 0.042$. We show the SSC model, derived in this case, as discussed in the text.

In this case the de-reddened optical–UV flux does not describe a $\nu^{5/2}$ law, being approximately intermediate between $\nu^{1/3}$ and ν^2. In Fig. 3 we show our synchrotron self-Compton model in this case: the parameters are similar to the ones used for Fig. 2, the differences being in the chosen values of $\gamma_{\rm min}$ (now equal to 100 for the 2000 s spectrum, 35 for the 7000 s spectrum and 7.1 for the 10^4–10^5 s spectrum). We had to change the size and the magnetic field value from $R = 7\times10^{11}$ cm and $B = 3\times10^5$ G for the 2000 s spectrum to $R = 2.5\times10^{11}$ cm and $B = 10^5$ G for the other two spectra. The other parameters are the same as for the model in Fig. 2.

Within this synchrotron self-Compton scenario the 'afterglow' of GRB 060218 is instead late prompt emission. The quasi-exponential decline in the X-ray light curve after roughly 3000 s is produced by the synchrotron tail going out from the observed 0.2–10 keV X-ray energy window, while the subsequent power-law decay is produced by the first-order self-Compton emission entering (and remaining) in this energy band. Since the electron distribution becomes steeper and steeper in time, this may explain why the temporal decay of the X-ray 'afterglow' seems normal, while the spectral slope is much steeper than in the majority of GRBs: being prompt emission, no closure relation can be applied to the light curve and spectrum of GRB 060218.

5 THE X-RAY BLACKBODY

Here we try to explain the nature of the soft blackbody ($kT \sim 0.1$–0.18 keV) component observed in the X-ray band up to 7000 s. It has been proposed that this soft X-ray thermal component corresponds to the shock breakout in a dense wind-like circumburst environment[2] (C06), although theoretical modelling seems to rule out this possibility (Li 2006). Alternative explanations (Fan et al. 2006) invoke the thermal emission from a hot cocoon (e.g. Ramirez-Ruiz, Celotti & Rees 2002) surrounding the jet. It was also proposed that the non-thermal prompt component observed in GRB 060218 might result from the bulk Comptonization of the soft X-ray thermal photons by a mildly relativistic jet (Wang et al. 2006).

Here we investigate whether the observed soft X-ray blackbody component might be interpreted within the classical GRB fireball model. We consider two possible scenarios, namely that the blackbody we see in the X-rays is the leftover from the initial acceleration, or that it is the result of some dissipation (Rees & Meszaros 2005; Peér, Meszaros & Rees 2006; Thompson 2006) occurring later, inside the star or in the vicinity of its surface. In the former case we expect that the *initial* blackbody has a large temperature and luminosity, while in the latter the blackbody 'degrades' much less, and the observed temperature and luminosity are not vastly different from their initial values.

In the case of an adiabatic expansion, due to the conversion of internal energy into bulk motion, the dynamics are controlled by four parameters: the initial radius R_0, the initial luminosity L_0 of the radiation assumed to be responsible for the expansion, the initial bulk Lorentz factor Γ_0 and the outflow mass rate $\dot M$, assumed to be constant during the expansion. The initial kinetic power of the material is $\dot E_{\rm kin,0} = \Gamma_0 \dot M c^2$. We then follow the usual prescription of an adiabatic expanding fireball.

According to this scenario, the temperature of the internal radiation is observed to be constant as long as we are in the acceleration phase, while it decreases as $R^{-2/3}$ between $R_{\rm acc} = \Gamma R_0/\Gamma_0$ (the radius where the acceleration ends) and R_τ, where the fireball becomes transparent (if $R_\tau > R_{\rm acc}$). The value of R_τ is (Daigne & Mochkovitch 2002; Meszaros 2006)

$$R_\tau = \frac{\sigma_{\rm T} Y \dot M_{\rm f,iso}}{8\pi m_{\rm p} c \Gamma^2} = \frac{\sigma_{\rm T} Y \dot E_{\rm k,iso}}{8\pi m_{\rm p} c^3 \Gamma^3} = 2.93\times10^{13}\,\frac{\dot E_{47,\rm iso}}{\Gamma^3}\ \mathrm{cm}, \qquad (1)$$

where $Y = 0.5$ is the number of electrons per baryon and $\dot E_{47,\rm iso}$ is the kinetic power of the fireball (i.e. $\dot E_{\rm k,iso} = \Gamma \dot M c^2$) in units of 10^{47} erg s^{-1}. At R_τ the observed blackbody temperature $T_{\rm ph}$ is

$$T_{\rm ph} = T_0 \left(\frac{R_{\rm acc}}{R_\tau}\right)^{2/3} \propto \left(\frac{R_0 \Gamma^4}{\Gamma_0 \dot E_{\rm kin}}\right)^{2/3}, \qquad (2)$$

where T_0 is the initial temperature. The photon number is conserved, hence

$$\frac{L_0}{T_0} \sim 4\pi \frac{R_0^2}{\Gamma_0^2}\sigma T_0^3 = \frac{L_{\rm ph}}{T_{\rm ph}} \rightarrow L_{\rm ph} = 4\pi \frac{R_0^2}{\Gamma_0^2}\sigma T_{\rm ph}^4 \left(\frac{R_\tau}{R_{\rm acc}}\right)^2. \qquad (3)$$

For any assumed value of R_0/Γ_0, from equations (2) and (3) one obtains T_0 and L_0 as a function of the observables $T_{\rm ph}$ and $L_{\rm ph}$. If we fix only Γ_0, then T_0 and L_0 are functions of R_0.

Furthermore, if the power of the fireball is the sum of its initial kinetic plus radiation powers, we can derive $\dot E_{\rm kin}$ and by knowing T_0 and $T_{\rm ph}$ we can derive the final value of Γ as a function of R_0, again for a specific value of Γ_0. Finally, knowing $E_{\rm kin}$ and Γ, we can derive $\dot M$.

All of these quantities are shown in Fig. 4 (as a function of R_0) for the specific choice of $\Gamma_0 = 1.225$, corresponding to an initial bulk velocity equal to the sound speed of a relativistic plasma. We can see that if we assume that the observed X-ray blackbody is the leftover of the initial radiation, injected at $R_0 \sim 10^6$ cm, then the required initial luminosity is very large, and since this power should last for an unusually long time (for this burst), the isotropically equivalent total energetics become huge. Consider instead values of R_0 around 10^{11} cm: in this case the blackbody is the result of some later dissipation, either in the fireball itself or resulting from the interaction of the fireball with the material forming the cocoon or at the surface of the star.

[2] Note that if instead the shock breakout happens in a normal stellar envelope, the required progenitor radius is $\sim10^{12}$ cm which is much larger than what is expected for an H–He envelope-stripped progenitor as suggested from spectroscopy (Pian et al. 2006).

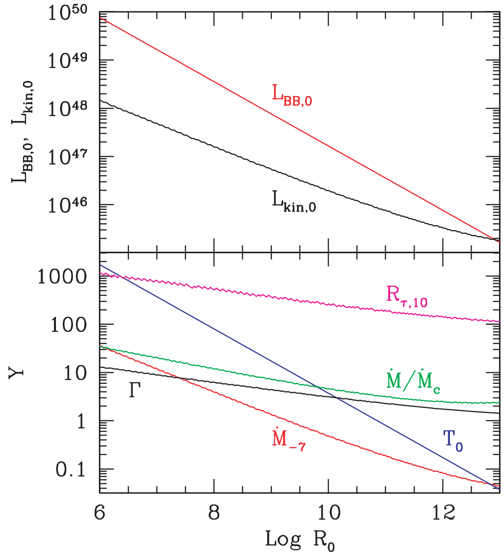

Figure 4. Top panel: the initial blackbody and kinetic powers as a function of the dissipation radius R_0, calculated assuming fixed values of the observed blackbody temperature (equal to 0.18 keV) and luminosity (equal to 8×10^{45} erg s^{-1}). We assumed an initial velocity equal to $\beta = 1/\sqrt{3}$ corresponding to $\Gamma_0 = 1.225$. Bottom panel: the mass outflow rate $\dot{M}$, the ratio $\dot{M}/\dot{M}_c$, the final bulk Lorentz factor Γ, the initial temperature T_0 and the transparency radius R_τ as a function of the dissipation radius R_0. Note that $\dot{M}_c$ is defined by setting $R_\tau = R_{acc}$. For $\dot{M}$ above $\dot{M}_c$ the material completes its acceleration before it becomes transparent, while the opposite occurs for $\dot{M} < \dot{M}_c$.

Since the dissipation occurs in this case much closer to the transparency radius, the blackbody does not 'degrade' much, being consistent with what we see without implying very large initial luminosities. For $R_0 \sim 10^{11}$ cm we have $\Gamma \sim 2$, $\dot{M} \sim 10^{-8}$ $M_\odot$ s^{-1}, T_0 around 1 keV and $R_\tau \sim 10^{12}$ cm.

6 SUMMARY AND CONCLUSIONS

We have studied the broad-band optical–UV to X-ray SED at three epochs which characterize different flux evolution phases observed (C06) in both the X-ray and optical–UV light curves up to 10^5 s. The spectrum shows a soft ($kT \sim 0.1$–0.18 keV) X-ray blackbody component (coupled with a typical non-thermal component) together with a Rayleigh–Jeans tail in the optical–UV band. Both of these components are almost steady in flux and slope, while the X-ray blackbody is undetected at late times (10^4–10^5 s). They have been interpreted (e.g. C06) as the shock breakout of the accompanying (nearly simultaneous) SN 2006aj. However, if the X-ray and optical–UV emission belong to the same blackbody emission (which we also exclude by direct spectral fitting), its energetics are even larger than the total kinetic energy of the supernova ejecta as derived from its late-time spectroscopy (e.g. Mazzali et al. 2006; Pian et al. 2006), and cannot be cured by relativistic beaming, since the supernova shock is not relativistic. Alternatively, only the X-ray or the optical–UV thermal component might be the shock breakout signal. The former possibility seems to be excluded both by detailed simulations (Li 2006) and because the supernova expansion velocity, derived from the X-ray blackbody fits, is too small compared with that derived from optical spectroscopy at late times (Pian et al. 2006). On the other hand, a shock breakout in the optical–UV band would imply too large a supernova expansion velocity to be consistent with the observed optical–UV early spectrum.

If the supernova shock breakout went undetected both in the optical–UV and in the X-ray band, we are left with two puzzling questions: (i) what is the nature of the observed early-time optical–UV emission (i.e. before the supernova radioactive decay emission sets in at 10^5 s), and (ii) what is the origin of the X-ray thermal component?

We have explored the possibility that the SED is produced by synchrotron self-Compton emission. A simple synchrotron fit to these data is satisfactory, with the optical–UV data corresponding to the self-absorbed synchrotron spectrum. Although the choice of the input parameter is not unique, the spectra at different times can be modelled by changing the slope of the electron distribution. A remarkable result of these fits is that the late-time (10^4–10^5 s) optical–UV emission should also be described by the same model (i.e. with the same parameters of the prompt emission, but with still steeper slopes of the electron distribution). The X-ray flux is in this case first-order self-Compton emission and naturally accounts for the unusually soft spectrum observed which is hardly reconcilable with the normal flux time decay within the context of the standard afterglow model (Fan et al. 2006).

Finally, we have considered the possibility that the blackbody observed in the X-ray band is a separate component. It is consistent with photospheric emission from the cocoon or some stellar material energized by the GRB jet. The origin of the blackbody photons should correspond to dissipation occurring not much below the photospheric radius of this material.

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