Did Swift measure gamma-ray burst prompt emission radii?

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ABSTRACT

The Swift X-Ray Telescope often observes a rapidly decaying X-ray emission stretching to as long as $t \sim 10^3$ s after a conventional prompt phase. This component is most likely due to a prompt emission viewed at large observer angles $\theta > 1/\Gamma$, where $\theta \sim 0.1$ is a typical viewing angle of the jet and $\Gamma \geq 100$ is the Lorentz factor of the flow during the prompt phase. This can be used to estimate the prompt emission radii, $r_{em} \geq 2c/\theta^2 \sim 6 \times 10^{15}$ cm. These radii are much larger than is assumed within the framework of a fireball model. Such large emission radii can be reconciled with a fast variability, on time-scales as short as milliseconds, if the emission is beamed in the bulk outflow frame, e.g. because of a random relativistic motion of ‘fundamental emitters’. This may also offer a possible explanation for X-ray flares observed during early afterglows.

Key words: gamma-rays: bursts.

1 INTRODUCTION

The recently launched Swift satellite (Gehrels et al. 2004), together with a network of ground-based observations, has been providing the scientific community with crucial information on gamma-ray bursts (GRBs). Besides the landmark detection of afterglows from short GRBs (e.g. Gehrels et al. 2005), Swift has gathered crucial data on the development of GRBs at early times. This is especially important since early observations provide clues to the properties of the ejecta, such as its composition, the lateral distribution of energy etc. At late times the energy is mostly transferred to the forward shock, the properties of which can hardly be used to probe the ejecta. A number of surprising results related to early afterglows have emerged (e.g. Tagliaferri et al. 2005; Nousek et al. 2005; Chincarini et al. 2005; O’Brien et al. 2005): (i) an early, $t \lesssim 10^4$ s, rapidly decaying X-ray component; (ii) X-ray flares occurring at $t \sim 10^2$–$10^3$ s; and (iii) a shallower than expected initial decay (or hump) of the afterglow. These features are common, but the light curves show a large variety. In this Letter we discuss the first two of the above-mentioned effects, i.e. a rapidly decaying component and X-ray flares, since both can be related to the prompt emission (as opposed to afterglow) and can thus be used to probe the ejecta and the central engine.

2 PROMPT EMISSION RADII

The initial fast-decaying part of afterglows can be a ‘high-altitude’ prompt emission, coming from angles $\theta > 1/\Gamma$ (Kumar & Panaitescu 2000; Barthelmy et al. 2005), where $\theta$ is the angle between the line of sight and the direction from the centre of the explosion towards an emitting point, and $\Gamma$ is the Lorentz factor of the outflow. For a $\delta$-function in time prompt emission pulse, after an initial spike the observed flux should decay as $t^{-\alpha}$, where $\alpha \approx 0.5$ is the spectral index of the prompt emission (Fenimore, Madras & Noyakshin 1998), roughly consistent with observations. One also expects that prompt and early afterglow emissions join smoothly, which seems to be generally observed (O’Brien et al. 2005).

[Exceptions, like GRB 050219a (Tagliaferri et al. 2005), may be due to interfering X-ray flares.]

If we accept the interpretation of the fast-decaying part as ‘high-altitude’ prompt emission, one can then determine the radii of the prompt emission and compare them with model predictions. The currently most popular fireball model (e.g. Piran 2004) relates the radii of emission $r_{em}$ to the variability time-scale $\delta t$ of the central source $r_{em} \sim 2\Gamma_0^2 \delta t$, where $\Gamma_0 \sim 100$–300 is the initial Lorentz factor. Within the framework of the fireball model this is also the variability time-scale of the prompt emission. Observationally, the prompt emission shows variability on time-scales as short as milliseconds, while most power is at a fraction of a second (Beloborodov, Stern & Svensson 1998). Adopting $\delta t \sim 0.1$ s, the prompt emission radius is $r_{em} \sim 6 \times 10^{15}$ cm ($\Gamma_0/100^2$). If the emission is generated at $r_{em}$ and is coming to the observer from large angles, $\theta > 1/\Gamma$, its delay with respect to the start of the prompt pulse is $t \sim (r_{em}/c)\theta^2/2$. If one can estimate $\theta$, then this can be used to measure $r_{em}$. This can be done from late ‘jet breaks’, giving typically $\theta \sim 0.1$ (e.g. Frail et al. 2001). Then, for the X-ray tail of the prompt emission extending to $t \sim 1000$ s, the implied emission radius is $r_{em} > 6 \times 10^{15}$ cm. This is much larger than is assumed in the fireball model. To make it consistent with the fireball model...
3 FAST VARIABILITY FROM LARGE RADI

If prompt emission is produced at distances $\sim 10^{15}$–$10^{16}$ cm, how can fast variability, on time-scales as short as milliseconds, be achieved? One possibility is that emission is beamed in the outflow frame, for example due to a relativistic motion of (using pulsar physics parlance) ‘fundamental emitters’ (Lyutikov & Blandford 2003). To prove this point, we consider a spherical outflow expanding with a bulk Lorentz factor $\Gamma$ with $N$ randomly distributed emitters moving with respect to the shell rest frame with a typical Lorentz factor $\gamma_T$. Highly boosted emitters, moving towards an observer, have a Lorentz factor $\gamma \sim 2\gamma_T\Gamma$ in the observer frame. If emission is generated at distances $r_{em}$, the observed variability time-scale can be as short as $\sim (r_{em}/c)/2\gamma^2 \approx (r_{em}/c)/(8\gamma_T\Gamma)^2$, so that modest values of $\gamma_T \sim 5$–10 $\ll \Gamma \sim 100$–300 would suffice to produce a short-time-scale variability from large distances $r_{em} \sim 10^{15}$–$10^{16}$ cm.

The model should satisfy a number of constraints. First, the number of sub-jets directed towards an observer from viewing angles $\theta < 1/\Gamma$ should be larger than unity (in order to produce at least one true prompt emission spike), but should not be too large, otherwise the prompt emission will be a smooth envelope of overlapping spikes. If a typical jet opening angle is $\theta_j$, then the number of sub-jets seen ‘head-on’ from angles $\theta < 1/\Gamma$ is

$$n_{prompt} \sim \frac{\pi N}{(\Gamma \gamma_j \theta_j)^2}.$$  

This should be larger than 1.

The second constraint that the model should satisfy relates to the efficiency of energy conversion. Suppose that the thickness of an outflowing shell in its rest frame is $L_{shell} \sim t_c\Gamma$, where $t_c$ is the source activity time ($t_c \sim 30$–1000 s for long bursts and $t_c \sim 1$ s for short bursts). Suppose then that fundamental emitters operate for a time $t_{pulse} = \eta L_{shell}$ in the flow frame, where $\eta$ is a dimensionless parameter. During this time the source can tap into energy contained within volume $\left( c t_{pulse} \right)^3$. The ratio of this volume times the number of emitters to the total volume of the shell is a measure of the efficiency of energy conversion into radiation:

$$\eta = \frac{N \left( c t_{pulse} \right)^3}{r_{em}^2 \theta_j^2 t_c \Gamma}.$$  

Since tapping of energy in the volume $\left( c t_{pulse} \right)^3$ is a definite upper limit on conversion efficiency, in the calculations we allow $\eta$ defined above to be slightly larger than unity.

To produce light curves we calculate the intensity of emission from sub-jets that are randomly located within the shell and moving in random directions with random Lorentz factors $1 < \gamma_T < \gamma_{T,max} = 5$. Each emitter is isotropic in its rest frame and is active for a random time $0 < t_{em} < 0.5\gamma_T t_c\Gamma = t_{pulse,max}$ in its rest frame. Dotted line: average intensity $\propto t^{-2.5}$, Dashed line: expected afterglow signal rising $\propto t^{-1.5}$ with arbitrary normalization. The homogeneous jet is centred on an observer with opening angle $\theta = 0.1$; dimensionless parameters are $n_{prompt} = 1.2$ and $\eta = 1.6$.

Along similar lines of reasoning, Lazzati & Begelman (2005) estimated prompt emission radii for the particular case of GRB 050315 for which a possible jet break is identified (Vaughan et al. 2006). The steep decay in that case is relatively short and lasts for 100 s, giving $r_{em} > 2.5 \times 10^{14}$ cm. Note that any observed duration of the steep decay phase provides only a lower limit on the prompt emission radius since the end of the steep decay may be related to emergent afterglow emission and not to the fact that the edge of the jet becomes visible (see Fig. 1). On the other hand, the late jet break time provides an estimate of the total opening angle of the jet. In any case, GRBs with a longer lasting steep decay phase, up to $10^3$ s, provide the most severe constraints on the models.

Thus the interpretation of the fast-decaying initial X-ray light curve as prompt emission seen at large angles can hardly be consistent with the fireball model. We should then either look for alternative possibilities to produce the fast-decaying part of the X-ray light curve (e.g. Mészáros & Rees 2001), or consider models that advocate production of prompt emission at larger radii; see Section 5.

3.1 Lateral dependence of prompt emission

Variations of the decay rate from the $t^{-(2+\alpha)}$ law may be used to probe the angular dependence $L(\theta_{axis})$ of the intensity of the prompt emission, where $\theta_{axis}$ is the angle between the axis of the explosion and an emitting point. Shallower decays can be due to e.g. a
structured jet, with $L \sim \theta_{\text{obs}}^{-2}$, observed outside some core: late-time emission then is coming from the more energetic part of the core. The effective emission intensity increases approximately as $\theta^2 \propto t$, and will result in an observed decay $t^{-1/2}$. Similarly, if the prompt emission is seen within a core, late emission comes from less energetic wings, giving in the case of a structured jet a flux $\propto t^{-1/2}$. Qualitatively, the relativistic internal motion of emitters makes it ‘easier’ to see the high-altitude emission.

To show this numerically we parametrize the number density of emitters as

$$n(\theta) \propto 1/\left(\theta^2 + \theta_0^2\right)^{2/3},$$

where $\theta_0$ is an angular core radius. (There are, naturally, other possible parametrizations, e.g. of the intensity of each emitter.) The results are presented in Fig. 2.

We can also expect deviations from a simple power-law decay due to the not exactly spherical form of the emitting surface. Such distortions are expected because of the development of the Kelvin–Helmholtz instability during an accelerating phase of the outflow. They will not be erased during the cooling stage because of causal disconnection of the points in the flow separated by angles $\Theta > 1/\Gamma$. Additional complications may come from the way in which the data analysis is performed, e.g. through a choice of the initial time trigger (Zhang et al. 2005; see also Lazzati & Begelman 2005).

4 ORIGIN OF X-RAY FLARES

Early X-ray light curves show complex behaviour with flares and frequent changes in temporal slope (e.g. O’Brien et al. 2005). Flares show very short rise and fall times, much shorter than the observation time after the onset of a GRB, while the underlying afterglow has the same behaviour before and after the flare (Burrows et al. 2005) (although there are exceptions). Both of these observations argue against a physical process in the forward shock. In addition, there is a hardening of the spectrum during X-ray flares (Burrows et al. 2005).

In the present model we interpret X-ray flares as being due to sub-jets located at large viewing angles, $\theta > 1/\Gamma$, but directed towards an observer. Randomly located, narrow spikes are clearly seen in the model light curves (Figs 1 and 2). In addition, as the flares are less de-boosted than the average high-altitude outflow, they will have a harder spectrum, as observed.

5 DISCUSSION

In this Letter we first point out that the interpretation of the initial fast-decaying part of the X-ray GRB light curves as a prompt emission seen at large angles, and a generic estimate of the opening angle of the jets, allows a measurement of the radius of prompt emission, which turns out to be relatively large, $>10^{15}$ cm. On basic grounds, gamma-ray emission should be generated before the deceleration radius $r_{\text{dec}} \sim (E_{\text{iso}}/4\pi\rho c^2 T_{\text{dec}}^2)^{1/3} \sim 10^{16} - 10^{17}$ cm, when most energy of the outflow is given to the surrounding medium (here $E_{\text{iso}}$ is the isotropic equivalent energy, $\rho$ is the density of the external medium, and $T_{\text{dec}}$ is the Lorentz factor at $r_{\text{dec}}$). The inferred emission radius is within this limit.

The estimate of the emission radius is very simple, and, in some sense, generic. It can hardly be consistent with the fireball model, unless extreme assumptions are made about the parameters (e.g. very large Lorentz factor). On the other hand, there are alternative models [e.g. the electromagnetic model (Lyutikov 2005a, see also Thompson 2005)] that place prompt emission radii at large distances, just before the deceleration radius $r_{\text{dec}}$.

Secondly, we show how models placing emission at large radii may be able to reproduce a short-time-scale variability of the prompt emission and explain later X-ray flares. This can be achieved if the prompt emission is beamed in the rest frame of the outflow, which may be due to an internal relativistic motion of ‘fundamental emitters’.

What can produce a relativistic motion in the bulk frame? It can be due, for example, to a relativistic Burgers-type turbulence (a collection of randomly directed shock waves). It is not clear how such turbulence may be generated. Alternatively, relativistic internal sub-jets can result from reconnection occurring in highly magnetized plasma with $\gamma \gg 1$, where $\gamma$ is a plasma magnetization parameter (Kennef & Corotni 1984). In this case the matter outflowing from a reconnection layer reaches relativistic speeds with $\gamma_{\text{out}} \sim \sigma$ (Lyutikov & Uzdensky 2003). Internal synchrotron emission by such jets, or Compton scattering of ambient photons, will be strongly beamed in the frame of the outflow. Note that this model does not require late engine activity to produce flares.

One of the main observational complications is that, at observer times larger than the conventional prompt phase, the X-ray light curve is a sum of the tail of the prompt emission, coming presumably from internal dissipation in the ejecta, and the forward shock emission. It is not obvious how to separate the two components. For example, GRBs that do not show a fast initial decay may be dominated by the forward shock emission from early on (O’Brien et al. 2005). This uncertainty also affects estimates of the emission radius, since the end of the steep decay may be related to the emergent afterglow emission and not to the jet opening angle (or the observer’s angle, in the case of a structured jet) – see Fig. 1. Another complication is that at these intermediate times, $10^3 < t < 10^4$ s, even the forward shock emission itself often does not conform to the standard afterglow models, showing flatter than expected profiles (e.g. Nousek et al. 2005).

1 Note that $r_{\text{dec}}$ defined above is independent of ejecta content, contrary to the claim in Zhang & Kobayashi (2005); see Lyutikov (2005a).
A consequence of the model is that some short GRBs may be just a single spike directed towards an observer of a long GRB. In our model the shorter spikes are highly beamed and less frequent, and produce harder emission. This can apply only to some short GRBs since as a class they are well established to have a different origin from long GRBs (from the non-observation of a supernova signature and the fact that they come from a distinctly different host galaxy population).

REFERENCES

Barthelmy S. D. et al., 2005, ApJ, 635, L133
Beloborodov A. M., Stern B. E., Svensson R., 1998, ApJ, 508, 25
Burrows D. N. et al., 2005, astro-ph/0511039
Chincarini G. et al., 2005, astro-ph/0511107
Fenimore E. E., Madras C. D., Nayakshin S., 1998, ApJ, 473, 998
Frail D. A. et al., 2001, ApJ, 562, 55
Gehrels N. et al., 2004, ApJ, 611, 1005
Gehrels N. et al., 2005, Nat, 437, 851
Kennel C. F., Coroniti F. V., 1984, ApJ, 283, 694
Kumar P., Panaitescu A., 2000, ApJ, 541, L51
Lazzati D., Begelman M., 2005, astro-ph/0511658
Lind K. R., Blandford R. D., 1985, ApJ, 295, 358
Lyutikov M., 2005a, astro-ph/0503505
Lyutikov M., 2005b, astro-ph/0512342
Lyutikov M., Blandford R., 2003, astro-ph/0312347
Lyutikov M., Uzdensky D., 2003, ApJ, 589, 893
Mészáros P., Rees M. J., 2001, ApJ, 556, L37
Nousek J. A. et al., 2005, astro-ph/0508332
O’Brien P. T. et al., 2005, astro-ph/0601125
Piran T., 2004, Rev. Mod. Phys., 76, 1143
Tagliaferri G. et al., 2005, Nat, 436, 985
Thompson C., 2005, astro-ph/0507387
Vaughan S. et al., 2006, ApJ, 638, 920
Zhang B., Kobayashi A., 2005, ApJ, 628, 315
Zhang B., Fan Y. Z., Dyks J., Kobayashi S., Meszaros P., Burrows D. N., Nousek J. A., Gehrels N., 2005, astro-ph/0508321

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