Death of Massive Stars: Supernovae and Gamma-Ray Bursts
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The soft X-ray landscape of gamma-ray bursts: thermal components

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Abstract. The repository of GRB (gamma-ray burst) observations made by the *Swift* X-ray Telescope, now consisting of over 650 bursts, is a valuable and unique resource for the study of GRB X-ray emission. The observed soft X-ray spectrum typically arises from an underlying power law continuum, absorbed by gas along the line-of-sight. However, particularly at early times in a burst's evolution the continuum emission is not always understood and may comprise multiple components including thermal emission unexpected in the standard model. A thermal X-ray component has been discovered in two very unusual GRBs, perhaps suggesting an association only with this subset of events. However, evidence exists for thermal emission from more typical examples and here we present a new discovery of one such case and describe a systematic search for thermal components among all early GRB X-ray spectra.

Keywords. gamma rays: bursts, X-rays: bursts

1. Introduction

The landmark discovery of thermal X-ray emission in the first few thousand seconds of the evolution of *Swift* GRB 060218 (Campana *et al.* 2006), followed four years later by a similar discovery in the spectra of GRB 100316D (Starling *et al.* 2011), were important steps in building a picture of the soft X-ray landscape of GRBs. However, both the origin and prevalence of such spectral components still evades understanding. GRBs 060218 and 100316D were classed as X-ray Flashes (XRFs), being softer and less energetic ($E_{\rm iso} \sim$ few $\times 10^{49}$ erg) when compared with their classical counterparts. They also had very long, > 1000 s, burst durations with more slowly evolving X-ray light curves than is typical (see Fig. 1), and are among the closest known GRBs at $z = 0.033$ and 0.059 respectively. Their blackbody temperatures appeared to cool over time, while the emitting radii increased (Campana *et al.* 2006; Olivares *et al.* 2012 and this volume). It is not clear whether this unusual pair defines a seperate class of transient objects or forms a subenergetic tail to the classical long GRB population. Possibly most importantly, these two objects are firmly associated with supernovae (SN), evident in optical spectroscopy (SN2006aj, Campana *et al.* 2006; Pian *et al.* 2006; Mazzali *et al.* 2006, and SN2010bh, Starling *et al.* 2011; Bufano *et al.* 2012), begging the question of whether the thermal X-ray components could be a part of the GRB-SN connection. If this tenth-of-a-keV blackbody-like emission were to come from the emerging supernova itself, as the shock front breaks out of the star (e.g. Nakar, this volume; Nakar & Sari 2012), then GRB X-ray emission could provide the earliest glimpses of these distant explosions.

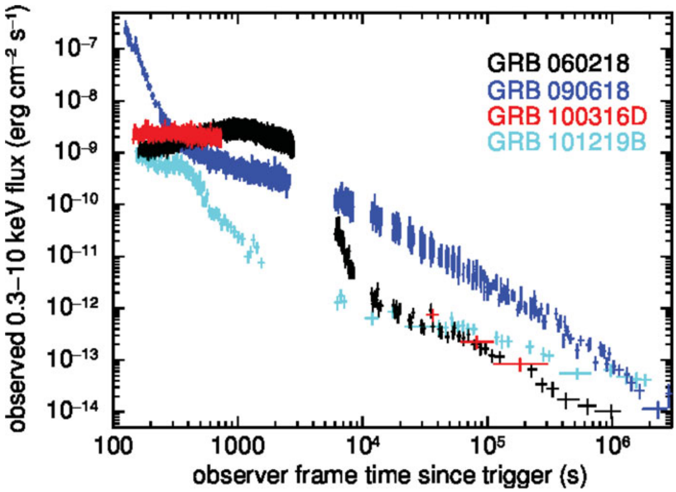

Figure 1. *Swift* X-ray light curves of the four GRBs reported to require thermal X-ray components in their early spectra: GRBs 060218 and 100316D show an initial flat evolution, GRB 090618 is initially the most X-ray bright and GRB 101219B (reported here) is initially the least X-ray bright and shows the slowest late-time decay.

X-ray emission from supernova shock breakouts had been predicted prior to the explosion of GRB 060218/SN2010bh, and was in fact observed serendipitously for SN2008D (Soderberg *et al.* 2008; Chevalier & Fransson 2008). Bromberg *et al.* (this volume) propose that these low luminosity events are in fact failed GRBs in which the jet could not break out of the star (Bromberg, Nakar & Piran 2011; Bromberg *et al.* 2012). Alternative explanations may lie in the central engine or cocoon emission.

The next development in this story came through a thorough analysis of GRB 090618. The early soft X-ray emission in this typical $z = 0.54$ GRB showed a more complex spectrum than could be fit with an absorbed power law. A thermal component was required, which had similar properties to those seen in the two earlier examples whilst being somewhat hotter (0.9 keV [restframe] cooling to 0.3 keV) and requiring larger radius and higher luminosity (see Page *et al.* 2011 for full details). This discovery suggested a link between the low luminosity events and classical long GRBs, although one should be careful in making this association before understanding of the origins of the thermal emission which could differ per GRB. Interestingly, GRB 090618 also has an associated SN, identified photometrically by Cano *et al.* (2011).

To investigate the extent of this phenomenon, we study the X-ray emission of SN-associated GRBs in detail, and have performed a systematic search for thermal X-ray components in all suitable GRBs from the large *Swift* X-ray Telescope (XRT) GRB Repository† (Evans *et al.* 2009).

2. GRB X-ray spectra

The basic shape The underlying GRB afterglow continuum in the 0.3–10 keV X-ray band takes the form of a power law or broken power law. This is expected in the fireball model (Sari 1997), where the interaction of the GRB jet with the surrounding medium results in a shock at which particles are accelerated producing synchrotron emission characterised by a set of power laws and breaks that move with time. The power law

† `www.swift.ac.uk/xrt_products/`

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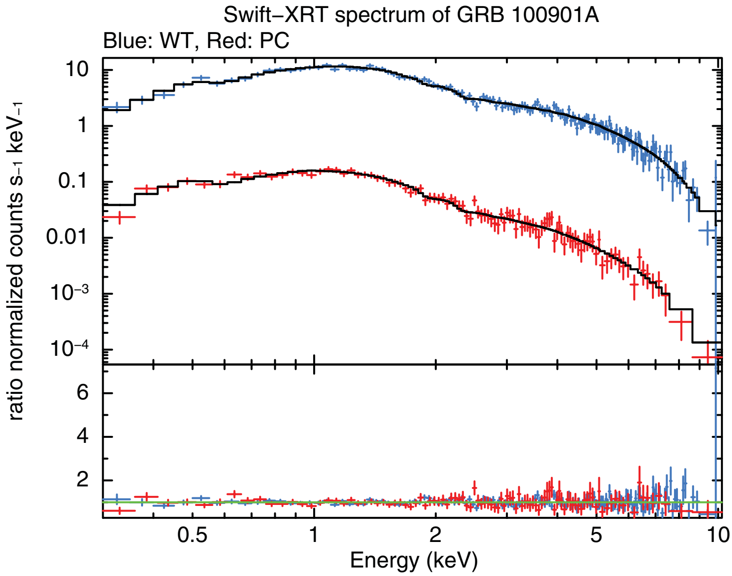

Figure 2. Example spectra from the *Swift* XRT GRB Repository. The early, Windowed Timing mode spectrum is shown in blue while the later, Photon Counting mode spectrum is shown in red. The lower panel shows the data to model ratio for an absorbed power law which is, in this case (GRB 100901A), an excellent fit. The curved profile of this spectrum is caused by a combination of instrumental response and absorption at soft X-ray energies by line-of-sight material.

is attenuated at soft X-ray energies (< 2 keV) by both Galactic and host galaxy absorbing gas, and potentially also by discrete intervening systems and/or the intergalactic medium. The total observed soft X-ray emission, 0.3–2 keV in *Swift* XRT data, could be a complex mix of evolving emission components and absorption components at varying redshifts, but in practice most GRB spectra can be adequately modelled with a single power law, Γ, absorbed by a fixed column of gas in our own galaxy, $N_{\rm H,Gal}$ as measured by Kalberla *et al.* (2005), plus an intrinsic column, $N_{\rm H,intrinsic}$, at the GRB redshift (Fig. 2).

The Swift XRT X-ray afterglow sample The GRB-dedicated *Swift* satellite (Gehrels *et al.* 2004) has been in operation since November 2004. The XRT (Burrows *et al.* 2005) takes data in two main operational modes, beginning in Windowed Timing (WT) mode for high count rates and automatically switching to Photon Counting (PC) mode as the GRB afterglow fades (Fig. 2). X-ray positions, light curves and spectra are among the automated science-grade products that are promptly available for each *Swift* XRT-detected GRB at the UK Swift Science Data Centre†, comprising a sample of over 650 GRBs (as of March 2012) suitable for statistical studies. Searching this database for excess soft X-ray emission above an absorbed power law which could be best fitted with a blackbody, we began a systematic search for further examples of thermal X-ray components in GRBs with known redshift (Sparre *et al.* in preparation).

† `www.swift.ac.uk`

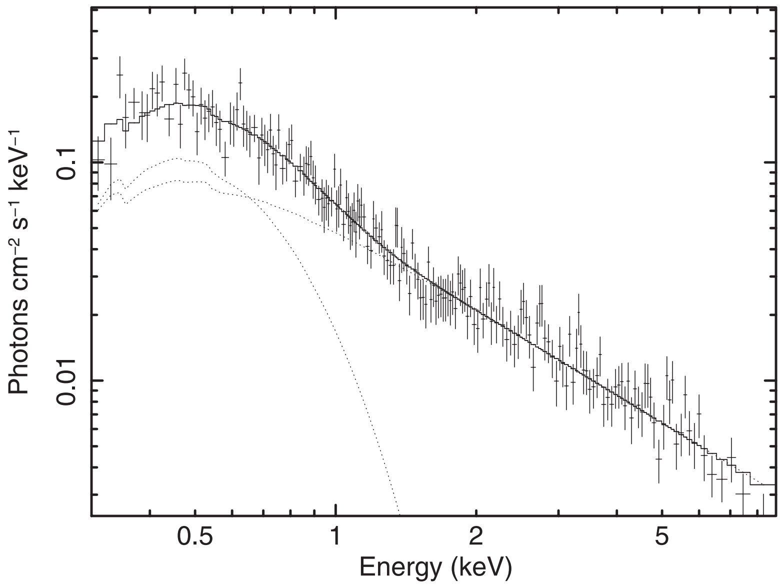

Figure 3. Average (160–540 s) *Swift* XRT WT mode spectrum of GRB 101219B. This spectrum is unfolded, meaning the instrumental response has been removed. The observed curvature here is largely due to absorption. The solid line shows the best fit absorbed BB+PL model, while the dashed lines show the conrtributions of the BB and PL respectively.

3. GRB 101219B: a new example of thermal X-ray emission

Our search revealed that a thermal X-ray component is required in GRB 101219B. We measure a temperature of 0.2 keV and corresponding luminosity 10^{47} erg s^{-1} for this blackbody; the unfolded X-ray spectrum is shown in Fig. 3. These properties are in the same ball-park as those measured for GRBs 060218, 100316D and 090618, whilst contributing the lowest fraction of the unabsorbed 0.3–10 keV flux (11% compared with 20% to $\geqslant$50%). This source lies at $z = 0.559$, comparable to GRB 090618, and has a spectroscopically identified SN (SN2010ma, Sparre *et al.* 2011). Its prompt emission properties cross the boundary between classical and low luminosity GRBs (e.g. $E_{\rm iso} \sim$ few $\times 10^{51}$ erg, see also Sakamoto, this volume), and the X-ray light curve can be compared with GRBs 060218, 100316D and 090618 in Fig. 1. This interesting discovery will be reported in detail in Starling *et al.* (in preparation).

4. Complicating factors and realistic limits on the recovery of similar blackbody components

In our search for further thermal X-ray components we take care to account for complexities which may affect spectral modelling, particularly at the earliest epochs and for the low luminosity events. These include tracking of spectral peak energy and flaring activity, and it is important to obtain as accurate as possible a measurement of absorbing column density and underlying continuum spectral shape. We fit the excess curvature of spectra with a single temperature perfect blackbody: this seems an simplistic way to represent this component but until we know its true origin we can only make this first approximation, which thus far fits the X-ray data well.

We have also performed monte carlo simulations to assess under which conditions a blackbody of the type discovered in GRB 101219B can be clearly recovered. Thus

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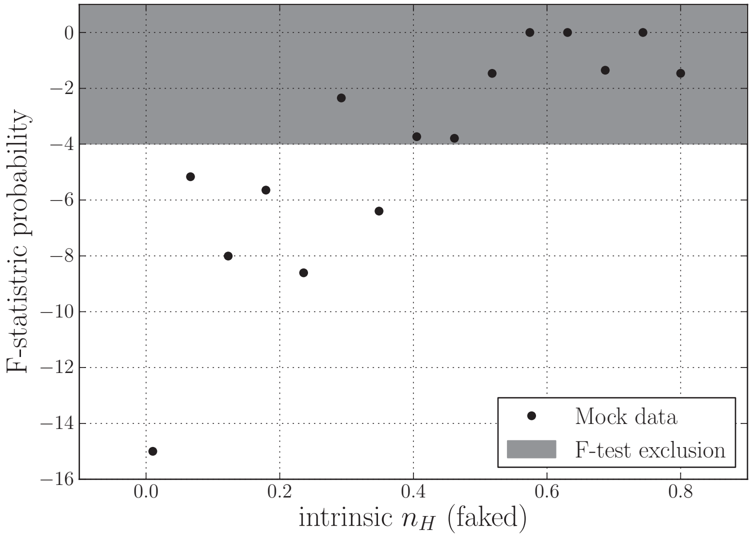

Figure 4. Simulated spectra reveal the conditions under which we might expect to recover a thermal component in *Swift* XRT data similar in nature to that found in GRB 101219B. In particular, a high intrinsic column density, $N_{\rm H,intrinsic} \geqslant 4 \times 10^{21}$ cm^{-2}, in GRB 101219B would have rendered us unable to unequivocally identify such a feature.

far the simulations are showing that we would be unable to identify such a component if the intrinsic column density were higher than around 4×10^{21} cm^{-2} (Fig. 4), while within a reasonable range the power law slope does not play a significant role in thermal component detectability. These results will appear in Sparre *et al.* (in preparation).

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Discussion

Katz: Is a 0.14 keV thermal component robustly measured in the spectrum?

Starling: Yes, I believe it can be. Of course you only see the high energy tail of it, and that itself is absorbed, but for example in GRB 060218 that 0.1–0.2 keV component completely dominated the soft X-ray flux for a time, and we get a consistent picture from the broadband data, seeing the thermal component cooling from ∼1–0.3 keV in 090618 and down into the UV/optical in 100316D and 060218. Even for the least prominent example the uncertainties on the BB temperature for example cannot be accounted for solely by say instrument calibration uncertainties.

Chornock: In addition to the fitting uncertainties, I am concerned about the physical interpretation. For example, 090618 has a BB radius of 6×10^{12} cm. What is your physical interpretation? This is larger than the expected radii of the progenitors.

Starling: I don't have a physical interpretation! Tomorrows' session will include discussion of shock breakout, proposed by some for 060218. The radius measured for that source ($\sim$ few $\times$ 10^{11} cm) by Campana *et al.* was, they said, consistent with the radius of a BSG or possibly a WR star with a thick wind. I agree you'd be having to stretch this for 090618 - it is the most extreme in its BB properties and will be interesting to see if/how it fits together with the low luminsoity GRBs.

Kawai: The spectrum modelled with an additional soft X-ray thermal model may also be modelled with a partial absorption model with a single power law emission component and patchy absorber.

Starling: We haven't tried complex absorption models - I suspect they would pose extra free parameters that would be difficult to cope with in typical GRB X-ray spectra. It is probable that absorption in more complicated than the Galactic+intrinsic model generally adopted, but in what way is difficult to determine until the advent of such missions as Athena.

Perley: Should we be concerned, when using $N_{\rm H}$ as a diagnostic of redshift or environment, that these estimates might be affected by an underlying thermal component? Can you rule out thermal emission for other GRBs?

Starling: No, for the vast majority of GRBs you don't need to worry. The afterglow will usually far outshine any thermal component. With our next set of simulations we will be able to set limits on the presence of thermal soft X-ray emission for any given burst, but we haven't done those yet.

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