THERMAL EMISSIONS SPANNING THE PROMPT AND THE AFTERGLOW PHASES OF THE ULTRA-LONG GRB 130925A

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ABSTRACT

GRB 130925A is an ultra-long gamma-ray burst (GRB), and it shows clear evidence for thermal emission in the soft X-ray data of the Swift/X-ray Telescope (XRT; ∼0.5 keV), lasting until the X-ray afterglow phase. Due to the long duration of the GRB, the burst could be studied in hard X-rays with high-resolution focusing detectors (NuSTAR). The blackbody temperature, as measured by the Swift/XRT, shows a decreasing trend until the late phase (Piro et al.) whereas the high-energy data reveal a significant blackbody component during the late epochs at an order of magnitude higher temperature (∼5 keV) compared to contemporaneous low energy data (Bellm et al.). We resolve this apparent contradiction by demonstrating that a model with two black bodies and a power law (2BBPL) is consistent with the data right from the late prompt emission to the afterglow phase. Both blackbodies show a similar cooling behavior up to late times. We invoke a structured jet, having a fast spine and a slower sheath layer, to identify the location of these blackbodies. Independent of the physical interpretation, we propose that the 2BBPL model is a generic feature of the prompt emission of all long GRBs, and the thermal emission found in the afterglow phase of different GRBs reflects the lingering thermal component of the prompt emission with different timescales. We strengthen this proposal by pointing out a close similarity between the spectral evolutions of this GRB and GRB 090618, a source with significant wide band data during the early afterglow phase.

Key words: gamma-ray burst: general – gamma-ray burst: individual (130925A) – methods: data analysis – methods: observational – radiation mechanisms: thermal

1. INTRODUCTION

The X-ray and gamma-ray emissions from gamma-ray bursts (GRBs) show two distinct phases: a prompt emission with drastic spectral and temporal variations, and an afterglow having smooth variation with time and energy (Piran 1999). Though the afterglow emission is understood to be due to synchrotron emission from a fast moving jet in the ambient medium, the characteristics and the radiation mechanisms of the prompt emission is still a matter of debate (Mészáros 2006). This apparent dichotomy in the observations, and the corresponding understanding, is accentuated by the fact that the prompt emission is studied using wide band hard X-ray/gamma-ray detectors with poor energy resolution and low sensitivity (due to high background), while the leisurely X-ray afterglow is amenable to be observed with focusing X-ray telescopes with excellent energy resolution and sensitivity. The fast moving Swift satellite (Gehrels et al. 2004) provides good quality data for the early afterglow of several GRBs in the low energies with the X-ray Telescope (XRT; Burrows et al. 2005). However, the typical slewing ability of the Swift (∼60–80 s) is insufficient to capture the prompt emission of the majority of GRBs with the XRT. Further, during the XRT observations, the hard X-ray emission fades below the detection level of Swift/Burst Alert Telescope (BAT; Barthelmy et al. 2005) for most cases. Hence, it is difficult to identify a broadband spectral feature with the combined BAT–XRT data.

In a recent paper (Basak & Rao 2014a, hereafter Paper I), we found clear evidence for two smoothly evolving blackbodies in the early afterglow of GRB 090618. As this GRB has a long gamma-ray duration, a significant overlap is seen in the BAT and XRT observations during the junction of the prompt and the afterglow phase (125–165 s). This overlapping observation allowed us to identify two blackbodies in the individual energy windows provided by the BAT and the XRT. The temperature and the flux of the two blackbodies are found to have similar evolution throughout the final pulse of the prompt emission until the early afterglow phase. This is one of the rare GRBs with a significant overlap in the XRT and BAT observations, and further, the two blackbodies happen to independently dominate the two detectors. Hence it is important to confirm this finding and examine whether this behavior is a generic feature of all GRBs.

In this context ultra-long GRBs, a class of GRBs that produces prompt emission for hours, provide an excellent opportunity to study the spectral evolution from the prompt to the afterglow phase. GRB 130925A is an ultra-long GRB with gamma-ray duration of ∼2 hr. This GRB was detected by several satellites including the Swift/BAT and the Swift/XRT. Due to its long-timescale gamma-ray emission, the burst could be observed with the focusing telescopes of NuSTAR (Harrison et al. 2013). Swift/XRT data revealed the presence of a blackbody emission at low energies during the prompt to the afterglow phase (Piro et al. 2014; P14 hereafter), though the same data could be interpreted as a steep power-law (PL) emission rather than a blackbody (Evans et al. 2014). The hard X-ray data from the NuSTAR, on the other hand, show a very significant emission above ∼10 keV at late times, which could be interpreted as due to an emission from a blackbody of temperature ∼5 keV (Bellm et al. 2014, B14 hereafter). The contemporaneous data of Swift/XRT, however, show a blackbody with temperature ∼0.5 keV (P14). In this paper, we demonstrate that all these data are consistent with a model consisting of two blackbodies and a power law (2BBPL). In the next section we summarize the pertinent data on GRB 130925A and present a re-analysis. The results are discussed in the context of a spine–sheath jet (Section 3), and in the last
section we give a summary of the important findings of this work.

2. THERMAL EMISSION IN GRB 130925A

GRB 130925A triggered the Swift/BAT at $T_0 = 2013$ September 25 04:11:24 UT. The Swift/XRT followed the burst from 150 s after the BAT trigger. The burst showed several pulse emissions and soft flares until a late time. A detailed analysis of the high-energy emission from this source is presented in Evans et al. (2014). They argue that this GRB, and by extension other ultra-long GRBs, could be understood as events with low circumburst densities, and correspondingly have an order of magnitude lower deceleration time compared to the normal long GRBs (however, see Schady et al. 2015). They strongly favor a steep PL function (index $\Gamma \sim -4$) for the X-ray afterglow spectrum and use the dust scattering model for the explanation (Shao & Dai 2007).

P14, on the other hand, explain the steep spectrum as a superposition of a blackbody (temperature, $kT \sim 0.5$ keV) and a power-law (BBPL) model. A crucial XMM-Newton observation after three months shows a harder PL index ($\sim -2.5$). As the thermal emission possibly subsides after such a long time, the spectrum is expected to reveal the underlying non-thermal component. The hard value of the index agrees with a standard afterglow in a wind medium. On the other hand, the blackbody component is suggested to be a “hot” cocoon that forms on the GRB jet as it pierces through the progenitor—possibly a blue supergiant star.

Another important clue to the spectral shape is provided by the observation with high-resolution focusing detectors: NuSTAR in three periods ($T_0 + 1.8$ days, $T_0 + 8.8$ days, and $T_0 + 11.3$ days) and Chandra ACIS-S in one period ($T_0 + 11.0$ days). B14 have analyzed the spectra in two epochs—$\sim 2$ days and $\sim 9–11$ days. In both cases, they found significant deviation from the canonical afterglow spectrum. The high-resolution data show a “dip” in the continuum spectrum. B14 used a BBPL model to capture the feature. Interestingly, they found that the blackbody temperature in the two epochs ($5.6^{+2.1}_{-1.2}$ keV and $4.0^{+0.1}_{-0.2}$ keV, respectively) have values an order of magnitude higher than that found by P14 in the XRT data. Though the data allow a softer blackbody (near $0.5$ keV), B14 argued in favor of the higher-temperature blackbody, as the lower-temperature blackbody shows an unphysical contraction of the apparent emitting region at the later epoch, from $(3.2 \pm 0.8) \times 10^{10}$ cm to $(1.7 \pm 0.4) \times 10^{10}$ cm.

2.1. Signature of Two Blackbodies in the Afterglow Data

To arrive at a correct spectral model, it is important to fix the continuum, and hence data above $\sim 10$ keV are very crucial. We re-analyze the data whenever a higher energy observation is available (either BAT or NuSTAR observation). These epochs are: (I) 150–300 s during the prompt emission (joint BAT–XRT observations), (II) 1.8 days during the afterglow (joint NuSTAR-XRT observations), and (III) $\sim 9–11$ days (joint Chandra–NuSTAR observations). The observation in epoch II provides the best possible data among all the observations due to the superior sensitivity and resolution of the NuSTAR detectors (and the higher flux compared to epoch III). In Figure 1, we show the spectrum of epoch II, fitted with various models. We follow the standard procedure described by B14 to extract the spectral data. The spectrum is fitted in XSPEC v12.8.2. We fit the following models: (A) PL, (B) PL with a Gaussian absorption (gabsxPL), (C) a blackbody with a power law (BBPL), and (D) two blackbodies with a power law (2BBPL). In all cases we have used a wabs and a zwabs model to account for the absorption in our Galaxy and in the source, respectively. P14 have fitted the time-resolved data during 20 ks–8 Ms with a wabsxzwabsxPL model. As the equivalent hydrogen column density ($N_H$) at the source should not change over time, they have linked this parameter in all time bins to obtain its precise value—$(2.1 \pm 0.1) \times 10^{22}$ cm$^{-2}$. We have used this value, along with the Galactic absorption of $1.7 \times 10^{20}$ cm$^{-2}$, to perform uniform fitting with all the models. Keeping the source absorption free gives a value close to P14, within the statistical errors. Note in Figure 1 (panel A) that a PL fit shows a “dip” near 5 keV. We obtain $\chi^2/\text{dof} = 158.7/124$ for a PL fit. Incidentally, a Band function (Band et al. 1993) gives a similar unacceptable fit with $\chi^2/\text{dof} = 153.0/121$. A Gaussian absorber gives an immediate improvement with $\chi^2/\text{dof} = 100.8/121$. However, as noted by B14, we also see a shift in the centroid from 6.4 $\pm$ 0.8 keV to $<4.0$ keV from epoch II to epoch III. Hence, the Gaussian absorber is unphysical. A BBPL model gives a reasonable fit with $\chi^2/\text{dof} = 106.1/122$ (see panel C). Finally, we fit the spectrum with a 2BBPL model and obtain $\chi^2/\text{dof} = 96.7/120$. The parameters of the blackbodies are shown in the first two rows of Table 1. We perform an F-test to find the significance of adding the second blackbody. We find a 2.9$\sigma$ significance corresponding to a $p$-value $= 3.8 \times 10^{-3}$. The temperature of the two blackbodies in this epoch are $5.1^{+1.7}_{-1.5}$ keV and $4.2^{+0.1}_{-0.1}$ keV. Note that these values are close to those reported by B14 and P14 (both within $1\sigma$), respectively. Based on the analysis of epoch II, we fit the spectrum of epoch III with a 2BBPL model. We freeze the PL index to the value obtained in epoch II ($\sim 3.74$). B14 has combined the NuSTAR data of $T_0 + 8.8$ and $T_0 + 11.3$ days. As both blackbodies may evolve significantly during this time, we use only the data of $T_0 + 11.3$ days. We obtain a $\chi^2/\text{dof} = 146.55/133$. The parameters of the blackbodies are shown in the last two rows of Table 1. The temperature of the two blackbodies are $3.0^{+0.5}_{-0.3}$ keV and $0.15 \pm 0.03$ keV. We note that the temperature of the high-temperature blackbody is somewhat lower than the temperature of the single blackbody as obtained by B14 ($4.0^{+0.4}_{-0.2}$).

2.2. Thermal Emission Spanning the Prompt and Afterglow Phase

In order to see how the temperature of the two blackbodies evolve during the prompt emission, we fit the joint BAT–XRT data in the 150–300 s interval. We obtain three time-resolved spectra in 150–175, 175–225, and 225–295 s intervals. For each case, we obtain a reasonable fit with reduced $\chi^2$ close to 1 for 76 dof (see Table 2). In the first interval, the 2BBPL model shows significant improvement compared to a BBPL model with $\Delta \chi^2 = 18.6$ at the expense of two dof. The F-test gives a $3.3\sigma$ significance ($p$-value $= 9.3 \times 10^{-4}$) for the addition of the second blackbody. It is worth mentioning that a Band function also gives an acceptable fit to the prompt emission data. However, as already mentioned the Band function is inadequate during epoch II, where we have good quality data. In addition to the joint BAT–XRT data, we also fit a BBPL model to the falling part of the final pulse (105–150 s) and obtain $kT = 12.9^{+4.0}_{-3.7}$ keV.
In Figure 2, we show the temperature evolution of the two blackbodies (filled symbols—circles for the higher-temperature blackbody and squares for the lower-temperature blackbody). The light curve (15–50 keV flux in units of erg cm\(^{-2}\) s\(^{-1}\)) of the GRB in the BAT and XRT detectors is shown in the background. The star represents the single blackbody temperature during the falling part of the last pulse in the BAT data. For comparison, we have plotted the temperature values obtained by P14 (open squares) and B14 (open triangles). We note that the values of the higher and the lower temperatures are in general agreement with those of B14 and P14, respectively. We fit the evolution of both blackbodies as a PL function of time. In doing this, we assume that all the blackbody temperatures given by P14 are that of the lower-temperature blackbody of the unified 2BBPL model. The slope of the evolution is \(-0.15 \pm 0.05\) and \(-0.20 \pm 0.02\) for the higher- and lower-temperature blackbody, respectively. The two evolutions can be considered to be either approximately similar or the higher-temperature blackbody to have a slower temperature evolution. Note that due to the large gap in the prompt and afterglow coverage of the high energy observation the error in the slope of the higher-temperature blackbody evolution is large. Hence, the comparison between the two temperature evolutions remains inconclusive. In the inset of Figure 2, we show the time evolution of the flux of the individual components of the 2BBPL model. We have shown only those points where we have high energy observation with either BAT or NuSTAR. In order to compare the flux evolution of the components, the blackbody flux is normalized to the PL flux of the initial time bin. We note that the thermal flux decreases more rapidly compared to the PL flux. The flux of the higher-temperature blackbody evolves even faster.

### 3. DISCUSSION

Though it is not conclusive that 2BBPL is the correct model for the GRB emission during the prompt and the early afterglow phases, there are strong evidences to support the claim that this model is consistent with a wide variety of data. This model is superior to other models (BBPL/Band) for bright GRBs (Rao et al. 2014) and it is a preferred model for GRBs with single pulses (Basak & Rao 2014b), GRBs with separable pulses (Basak & Rao 2013b), and GRBs with high energy (GeV) emission and detected by Fermi/Large Area Telescope (Basak & Rao 2013a). For GRB 090618 (Paper 1), the superior
Note that the size of the emitting regions calculated above are not directly tied to the actual sizes of the outflows. The observed physical sizes of the two blackbodies show very slow expansion rates and the corresponding sizes of the outflows plasma. Hence the photospheres would also have slow speeds and hence they cannot be tied to the actual sizes of the outflowing plasma. The radius of the higher-temperature blackbody in the two epochs is found to be $R_{BB} = (0.9 \pm 0.3) \times 10^8$ cm and $R_{BB} = (1.3 \pm 0.2) \times 10^8$ cm, which shows a slow increment. Interestingly, the value of the lower-temperature blackbody $R_{BB}$ is found to be $R_{BB} = (2.0 \pm 1.0) \times 10^{10}$ cm and $R_{BB} = (2.0 \pm 1.0) \times 10^{10}$ cm (see the last column of Table 1). Note that this result is markedly different from that obtained by B14 and P14. Our analysis shows a definite increment of the apparent radius at the later epoch.

3.2. A Spine–Sheath Jet

In Paper I, we proposed a spine–sheath jet to explain the evolution of the two blackbodies. A fast moving spine with a slower sheath component is expected in a number of physical scenarios, e.g., a hot cocoon formed over the GRB jet as it pierces through the envelope of the progenitor (Mészáros & Rees 2001; Ramirez-Ruiz et al. 2002; Zhang et al. 2003, 2004), or a collimated proton jet along with a wider neutron sheath for a magnetic jet (Vlahakis et al. 2003; Peng et al. 2005). Such a structured jet is frequently invoked to explain a double jet break and optical re-brightening (e.g., Berger et al. 2003; Liang & Dai 2004; Holland et al. 2012). If the sheath component of the jet is in fact the cocoon, we expect it to be less collimated and the terminal bulk Lorentz factor ($\eta$) to be lower by a factor of $\sim 10$ than the spine.

The observed physical sizes of the two blackbodies show very slow expansion rates and the corresponding sizes of the photospheres would also have slow speeds and hence they cannot be tied to the actual sizes of the outflowing plasma. Hence the photospheres have to be steady/gradually changing regions in the outflow. We note that the spine photosphere produces the higher-temperature blackbody while the lower-temperature blackbody is produced by the sheath photosphere. Note that the size of the emitting regions calculated above are considered to be spherical emission regions. The physical photosphere can be related to the observed size as $r_p = \eta R_{BB}$. With reasonable values of $\eta$ for the spine and the sheath (say, $10^3$ and $10^2$, respectively), one should obtain larger values of $\eta R_{BB}$.

### Table 2

| Parameter | 105–150 s | 150–175 s | 175–225 s | 225–295 s |
|-----------|-----------|-----------|-----------|-----------|
| $n_B$ (10$^{22}$ atoms cm$^{-2}$) | ... | $2.1 \pm 0.2$ | $1.7 \pm 0.2$ | $1.7 \pm 0.2$ |
| $kT$ (keV) | $13.0^{+4.0}_{-3.7}$ | ... | ... | ... |
| $N$ | $0.11^{+0.09}_{-0.06}$ | ... | ... | ... |
| $kT_h$ (keV) | ... | $8.9^{+1.8}_{-1.7}$ | $7.0^{+5.8}_{-3.5}$ | $8.5^{+4.6}_{-4.1}$ |
| $N_h$ | ... | $0.11^{+0.05}_{-0.04}$ | $(3.5 \pm 3.2) \times 10^{-2}$ | $(3.2 \pm 3.3) \times 10^{-2}$ |
| $kT_l$ (keV) | ... | $2.1^{+0.5}_{-0.6}$ | $2.1 \pm 0.5$ | $2.3^{+0.5}_{-0.7}$ |
| $N_l$ | ... | $0.14^{+0.07}_{-0.06}$ | $(7.6^{+3.5}_{-2.2}) \times 10^{-2}$ | $(7.7^{+3.5}_{-2.2}) \times 10^{-2}$ |
| $\Gamma$ | $-2.3 \pm 0.2$ | $-2.2 \pm 0.1$ | $-2.1 \pm 0.1$ | $-2.1 \pm 0.1$ |
| $\chi^2_{red}$ (dof) | 0.93 (54) | 1.2 (76) | 1.3 (76) | 1.1 (76) |

Note. $h =$ Higher-temperature blackbody, $l =$ Lower-temperature blackbody.
the corresponding emission radius. The observed properties of the two photospheres can be used to constrain the properties of the spine and the sheath. For example, we have found that the higher-temperature blackbody has a much slower evolution and hence we can assume that the spine remains “steady” for a long time. The sheath photosphere, on the other hand, shows considerable evolution. For a cocoon sheath, a rapid photospheric expansion is indeed expected (Starling et al. 2012).

3.3. Comparison with GRB 090618

Evans et al. (2014) systematically analyzed 672 XRT GRBs, and found that after 3 ks of the individual trigger, the hardness ratio (HR) does not show any evolution for the majority of GRBs. For 12 GRBs (including GRB 130925A), which show >5σ significance of HR variation at late times, the PL index shows a continuous increment with time. They argue that the HR evolutions in these GRBs including GRB 130925A can be explained by a dust scattering model.

However, the hard X-ray data at late times require emission above 10 keV, which is not compatible with a steep PL model (as required by the XRT data alone). Hence, we explore here whether the spectral evolution of GRB 130925A could be explained by the 2BBPL model and whether this model is a generic feature of all GRBs. We have taken the temperature evolution as given in Figure 2, and verified that the count rate variation in two energy bands in the XRT data (0.3–1.5 and 1.5–10 keV) after 100 ks is compatible with the flux variation of the three components as given in the inset of Figure 2.

The rare occurrence of spectral variation after 3 ks could be explained by postulating that the blackbody components decay at different rates for different GRBs. We investigate this hypothesis by comparing the results of GRB 130925A with those of GRB 090618. In Figure 3, we plot the relevant parameters for these two GRBs, but the time axis of GRB 090618 is arbitrarily stretched (100–300 s data are stretched to 100–2 × 10^7 s). The close similarity of the spectral variation of these two GRBs encourages us to hypothesize that the 2BBPL model is a generic feature of all GRBs and the blackbody components decay at different rates for different GRBs.

4. CONCLUSIONS

The major conclusions from the work presented here can be summarized as follows.

1. We use high-resolution *NuSTAR* data of the ultra-long GRB 130925A, and find that the spectrum is consistent with a 2BBPL model. The lower-temperature blackbody is consistent with an evolving blackbody throughout the burst (P14). The higher-temperature blackbody is also consistent with the single blackbody of B14, and this component also shows a similar evolution to the lower-temperature blackbody.
2. The evolution of the corresponding photospheres of the two blackbodies is found to be different. While the higher-temperature blackbody shows a constant spherical emission region, the lower-temperature blackbody shows a rapid evolution of the photosphere.
3. We have proposed a structured jet with a fast spine and slow sheath as the origin of the thermal components. The higher-temperature blackbody is produced at the spine photosphere, which remains “steady” at the later epoch.

The sheath is possibly a cocoon, which shows a rapid expansion of the photosphere.

In recent years, we have found that the time-resolved prompt emission spectrum of a variety of GRBs is consistent with the 2BBPL model (Basak & Rao 2013a, 2013b; Rao et al. 2014; see also Iyyani et al. 2015). This spectral shape is statistically preferred for GRBs with high signal-to-noise data. However, due to the limited spectral resolution of the gamma-ray detectors, we could not draw a firm conclusion. We could detect the two blackbodies in the early afterglow data of GRB 090618 (Paper I), as the XRT provided good spectral data during the overlapping observation with the BAT. The current observation also shows a clear signature of the two blackbodies that evolve from the very early phase during the prompt emission and which remains visible with high significance at very late times. We emphasize again that independent of the physical interpretation of the 2BBPL, this model emerges as a generic spectrum of long GRBs.

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REFERENCES

Band, D., Matteson, J., Ford, L., et al. 1993, *ApJ*, 413, 281
Barthelmy, S. D., Barbier, L. M., Cummings, J. R., et al. 2005, *SSRv*, 120, 143
Basak, R., & Rao, A. R. 2013a, *ApJ*, 775, 31
Basak, R., & Rao, A. R. 2013b, *ApJ*, 768, 187
Basak, R., & Rao, A. R. 2014a, ApJ, submitted (arXiv:1409.4538)
Basak, R., & Rao, A. R. 2014b, MNRAS, 442, 419
Bellm, E. C., Barrière, N. M., Bhalerao, V., et al. 2014, ApJL, 784, L19
Berger, E., Kulkarni, S. R., Pooley, G., et al. 2003, Natur, 426, 154
Burrows, D. N., Hill, J. E., Nousek, J. A., et al. 2005, SSRv, 120, 165
Evans, P. A., Willingale, R., Osborne, J. P., et al. 2014, MNRAS, 444, 250
Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, ApJ, 611, 1005
Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, ApJ, 770, 103
Holland, S. T., De Pasquale, M., Mao, J., et al. 2012, ApJ, 745, 41
Iyyani, S., Ryde, F., Ahlgren, B., et al. 2015, MNRAS, 450, 1651
Liang, E. W., & Dai, Z. G. 2004, ApJL, 608, L9
Mészáros, P. 2006, RPPh, 69, 2259
Mészáros, P., & Rees, M. J. 2001, ApJL, 556, L37
Peng, F., Königl, A., & Granot, J. 2005, ApJ, 626, 966
Piran, T. 1999, PhRv, 314, 575
Piro, L., Troja, E., Gendre, B., et al. 2014, ApJL, 790, L15
Ramirez-Ruiz, E., Celotti, A., & Rees, M. J. 2002, MNRAS, 337, 1349
Rao, A. R., Basak, R., Bhattacharya, J., et al. 2014, RAA, 14, 35
Schady, P., Kruehler, T., Greiner, J., et al. 2015, A&A, submitted (arXiv:1505.04415)
Shao, L., & Dai, Z. G. 2007, ApJ, 660, 1319
Starling, R. L. C., Page, K. L., Pe’Er, A., Beardmore, A. P., & Osborne, J. P. 2012, MNRAS, 427, 2950
Vlahakis, N., Peng, F., & Königl, A. 2003, ApJL, 594, L23
Zhang, W., Woosley, S. E., & Heger, A. 2004, ApJ, 608, 365
Zhang, W., Woosley, S. E., & MacFadyen, A. I. 2003, ApJ, 586, 356