Thermal components in the early X-ray afterglows of GRBs

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The early X-ray afterglows of GRBs are usually well-described by a simple absorbed power-law. However, in 2006, in the afterglow of GRB 060218, it was shown that an additional component in the form of blackbody was required to explain the spectra. Since then there has been a dozen other reports of thermal components in the early X-ray afterglows of GRBs. The origin of this emission is still unclear, with proposed explanations including supernova shock breakout, the cocoon surrounding the jet or emission from the jet itself. In this work we present a systematic study of 74 GRBs with known redshifts observed by Swift XRT in a search for thermal components in the early X-ray afterglows. We report six detections in our sample, and also confirm an additional three cases that were previously reported in the literature. We explore their common properties and find that the majority of these bursts have a narrow span of radii, while at the same time having a wide spread in luminosities. From these results we infer that a likely explanation for the thermal emission is the cocoon breaking out from a thick wind that surrounds the progenitor star. For two of the bursts an explanation in terms of late prompt emission from the jet is instead more likely.

Keywords: Gamma-ray bursts, afterglow, thermal component, X-rays

1. Introduction

The emission coming from GRBs is usually divided into two main phases: the prompt emission and the afterglow (for a detailed review reader is further referred to 1). The prompt emission is observed mainly in gamma-rays, it lasts up to couple of minutes and is characterized by a variable light curve. The afterglow of GRBs arises from the interaction between the jet and the circum-stellar medium (CMS). This phase can last up to years, it is observed from X-rays to radio wavelengths and, unlike the prompt emission, is characterized by a more smooth behaviour. In this work we are using X-ray observations made by *Swift* satellite X-ray Telescope (XRT)[2]. The canonical XRT light curve is composed of four parts: a steep decay, a shallow decay, a normal decay and a post-jet break component[3]. In this work only the first two parts of the XRT light curve are relevant. The spectra of early X-ray light curves are usually well described by power laws. The origin of the power-law spectrum is described as a synchrotron emission when the spectrum is observed in a limited energy range, typically from 0.3 - 10 keV (for details see 4). The observations of a nearby, low-luminosity GRB 060218 showed a presence of a thermal component in the early X-ray spectra 5. Following this detection there have been a dozen of other detections of thermal components in the early X-ray afterglows (6 7, 8, 9, 10, 11). An origin of the thermal comonent due to SN shock break-out was suggested for GRB 060218[5]. However, this explanation faces difficulties in explaining the high observed luminosities reported in other cases with $L_{BB} > 10^{47}$ergs^{-1}. Other possible explanation that were suggested are that the thermal component originates from the cocoon surrounding the jet (12, 13) or the jet itself (10, 14, 11).

In order to evaluate different models for the origin of the thermal component a bigger sample of detections is needed with addition of time-resolved measurements. To do this we performed the time-resolved analysis of 74 GRBs observed by *Swift* XRT between 2011 and end of 2015. We compared the absorbed power-law with the absorbed power-law plus a blackbody model. The significance of the added compoent was determined using Monte Carlo simulations.

2. Data Sample And Data Analysis

Our sample of analyzed GRBs consists of GRBs that have fullfilled following criteria:

- known spectroscopic redshif
- *Swift* XRT window timing (WT) mode data available
- observed between 2011-01-01 and 2015-12-31
- observed time-averaged WT mode flux higher than 2×10^{-10}erg cm^{-2} s^{-1}

All GRBs that met the above criteria were long GRBs. Data reduction was performed locally, with special atention being paid to pile-up and redistribution issues at lower enegies (< 0.5 keV). All data are grouped such that 20 counts occupies one bin which allows for the use of χ^2 statistics.

Data analysis was primarily time-resolved. Each time-resolved spectrum was produced using Bayesian blocks algorithm[15]. This method was selected due to the fact that by using Bayesian blocks we obtained a significantly higher time resolution than in previous studies. Another difference between our approach and previous ones is that we have not excluded any intervals that contain flares or other untypical behaviour in the light curve. Below 2 keV Galactic as well as intrinsic H column densities are important and we used *tbabs* and *ztbabs* models in XSPEC. The Galactic column density was calculated using the tool $N_{H,tot}$ available on the *Swift* website which includes contributions from both atomic and molecular H (for details see 16). In determining the intrinsic H column density we made an assumption that it stays constant for the duration of the observation. The intrinsic H column density was derived separately depending on the model in order to avoid the possibility of a blackbody presence increasing the value of the intrinsic H column density when fitting with only a power law. We have fitted all spectra with an absorbed power law and an absorbed power law plus a blackbody at the redshift ot the host galaxy. In order to assess the significance of the blackbody component we performed Monte Carlo simulations. For each spectrum we have simulated 10 000 fake spectra from the best-fitting parameters of the power-law model using XSPEC fakeit command and the response files from the real data, while background was also simulated.

3. Results And Discussion

In order to say that the thermal component is significant we used a criterion that the blackbody component should be significant at $> 3\sigma$ in at least three consecutive time bins. With this criterion we have identified six GRBs in which the thermal component is present: GRB 111123A, GRB 111225A, GRB 121211A, GRB 150727A and GRB 151027A. Also, we have confirmed three previously reported GRBs with a significant thermal component: GRB 060218, GRB 090618 and GRB 101219B.

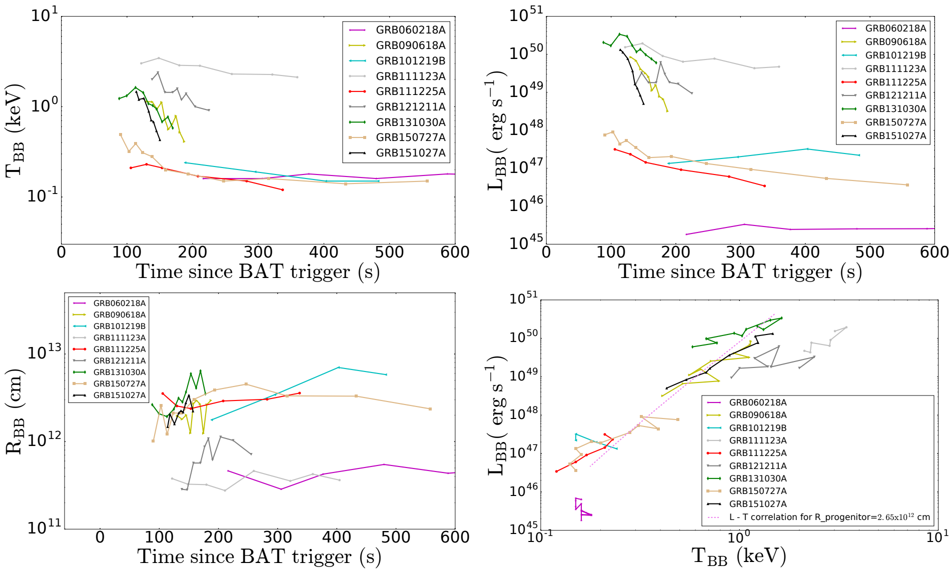

Fig. 1: Properties of the blackbody parameters in GRBs with significant detections. Top left: time evolution of the temperature. Top right: time evolution of the luminosity. Bottom left: time evolution of the radius. Bottom right: the correlation between temperature and luminosity. Error bars are omitted from this figure for clarity.

In order to compare the properties of all GRBs with the detected thermal components we plotted the blackbody parameters together, as shown in Fig.1. The top panels show the time-evolution of blackbody temperatures and luminosities while the bottom ones show the time-evolution of blackbody radii as well as the relation between temperatures and luminosities. What can be seen from the Fig.1 is that the luminosities of the blackbody are spanning a wide range $10^{49} - \times 10^{50}$erg s^{-1}, while at the same time radii occupy a narrow range $7 \times 10^{11} - 5 \times 10^{12}$cm. The lower right panel of Fig.1 shows that the majority of bursts roughly fall along a $L \propto T^4$ correlation, where the dashed line is the relation $L = \sigma 4\pi R^2 T^4$ with $R = 2.65 \times 10^{12}$ cm (note that this line is not a fit). This fact is noteworthy and points to an origin of the thermal component connected to a characteristic radius of the progenitors. We suggested that these observations may be explained by a cocoon breaking out from a thick wind that surrounds the progenitor. In the Fig.1 three GRBs clearly stand out: GRB 060218, GRB 111123A and GRB 121211A. The first one is a well know low-luminosity burst, while the latter two have irregular light curves with flares and the emission from these two bursts is most likely due to late prompt emission from the jet itself.

The number of thermal components identified in our sample of 4 years of data correspond to a detection rate of 8 per cent. We found that thermal components are preferentially detected at lower redshifts ($z \lesssim 1$) and low intrinsic H column densities ($\leq 1 \times 10^{22}\mathrm{cm}^{-2}$). We have also found that the GRBs with significant thermal components have low X-ray luminosity compared to the sample as a whole. However, it needs to be emphasized that the sample of nine GRBs is small and the bigger sample is needed in order to examine whether the narrow span of blackbody radii will persist with more added data.

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