Are GRB Blackbodies an Artifact of Spectral Evolution?

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ABSTRACT

The analysis of gamma-ray burst (GRB) spectra with multi-component emission models has become an important part of the field. In particular, multi-component analysis where one component is a blackbody representing emission from a photosphere has enabled both a more detailed understanding of the energy content of the jet as well as the ability to examine the dynamic structure of the outflow. While the existence of a blackbody-like component has been shown to be significant and not a byproduct of background fluctuations, it is very possible that it can be an artifact of spectral evolution of a single component that is being poorly resolved in time. Herein, this possibility is tested by simulating a single component evolving in time and then folding the spectra through the Fermi detector response to generate time-tagged event Gamma-ray Burst Monitor (GBM) data. We then fit both the time integrated and resolved generated spectral data with a multi-component model using standard tools. It is found that in \textit{time-integrated} spectra, a blackbody can be falsely identified due to the spectral curvature introduced by the spectral evolution. However, in \textit{time-resolved} analysis defined by time bins that can resolve the evolution of the spectra, the significance of the falsely identified blackbody is very low. Additionally, the evolution of the artificial blackbody parameters does not match the recurring behavior that has been identified in the actual observations. These results reinforce the existence of the blackbody found in \textit{time-resolved} analysis of GRBs and stress the point that caution should be taken when using time-integrated spectral analysis for identifying physical properties of GRBs.

Key words: (stars:) gamma ray bursts – methods: data analysis – radiation mechanisms: thermal

1 INTRODUCTION

Thermal emission from gamma-ray bursts (GRBs) was one of the earliest predictions when models were first formulated to explain these extreme astrophysical events (Goodman 1986; Paczynski 1986). In principle, thermal emission from the jet photosphere is a natural explanation for the emission because the GRB jet starts its expansion optically thick and as it evolves to lower densities the thermal energy trapped in the flow is released. In certain scenarios, this energy is in the form of a blackbody (Beloborodov 2010; Lundman, Pe’er & Ryde 2014). However, once broadband observations of thousands of GRB prompt γ-ray spectra were analyzed, it was found that the majority of the spectra were non-thermal (Mazets et al. 1981; Fenimore et al. 1982; Matz, Forrest & Vestrand 1985). There were noted exceptions having blackbody spectra (Ghirlanda, Celotti & Ghisellini 2003; Ryde 2004), while in others at least part of the spectrum appeared to contain a combination of thermal and non-thermal emission (Ryde 2005; Ryde & Pe’er 2009). Then observations with the Fermi Gamma-ray Telescope confirmed the existence of a blackbody component in addition to the typically observed Band component (Band, Matteson & Ford 1993) in several GRBs (Guiriec et al. 2011; Axelsson et al. 2012; Preece et al. 2014; Burgess et al. 2014; Iyyani et al. 2013). The existence of the component was shown to be statistically significant to at least 5σ in some cases. Additionally, Ghirlanda, Pescalli & Ghisellini (2013) showed that evidently some GRBs which have a very narrow and hard spectrum can be well fitted by a blackbody alone and constitute a very small fraction of all GRBs in line with earlier observations. Even though pure blackbody spectra are rare, it is important to note that the existence of such GRBs confirms the early idea that emission from the photosphere does indeed play a role in shaping GRB spectra. This strongly motivates the search for blackbody components in non-thermal appearing GRBs as well.
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The identification of this blackbody component in GRB spectra is a crucial element in determining the origin, kinematics, structure, and emission mechanisms of these events. For example, it has been shown that measuring the flux of the thermal and non-thermal components allows determination of the photospheric radius ($r_{ph}$) and bulk jet Lorentz factor ($\Gamma$) of the GRB jet (Pe'er et al. 2007). The very presence of the thermal component eliminates many emission models and constrains the amount of energy that is available for the acceleration of particles to high-energies via dissipation. It suggests the at least part of the emission site is in the optically thick region of the flow. Moreover, these observations are a highlight of the Fermi gamma-ray space telescope mission and have enabled a greater understanding of GRBs.

Such an important discovery warrants a deep investigation into the reliability of the observation. As stated above, the significance of the thermal component has been tested (Guiriec et al. 2011; Axelsson et al. 2012) for example and hence been shown not to be an artifact of background fluctuations. Moreover, calibration errors have been ruled out. However, it is possible that the component could be present in the spectra as an artifact of the spectral evolution of a single non-thermal component. Herein, this assumption is tested by simulating GRB pulses with known spectral evolution of a single Band component. The pulses are fit with both Band and Band+blackbody models in an attempt to find a blackbody where one does not actually exist.

2 GENERAL FEATURES OF THE BLACKBODY COMPONENT

While the detection of a blackbody in GRB spectra has several implications for the physics of GRBs in itself, it is also important to discuss how it alters the typical Band fits. In general, GRB spectra fit with the Band function have a low-energy index ($\alpha$) inconsistent with what is expected from the simplest synchrotron models (Preece et al. 1998) (see; however, Daigne, Bosnjak & Dubus 2011). When a blackbody is added to the spectrum below the $\nu F_\nu$ peak, it can alter the value of $\alpha$, possibly making it consistent with synchrotron. This could be a resolution of the so-called synchrotron “line-of-death” problem. Additionally, the $\nu F_\nu$ peak ($E_p$) of the Band component can be shifted to higher energies, when it is fit with a blackbody. This type of behavior has been observed in several Fermi GRBs (Guiriec et al. 2011; Axelsson et al. 2012). These features, along with past theoretical predictions (Goodman 1986; Paczynski 1986; Beloborodov 2010; Lundman, Pe'er & Ryde 2014), strongly motivate multi-component fitting where one component is a blackbody.

The evolution of $kT$ has been well documented (Axelsson et al. 2012; Ryde 2005; Burgess et al. 2014; Iyyani et al. 2013) and shown to universally decay as a broken power law in single pulses of GRBs (see Figure 1). Apart from the statistical significance of the blackbody component, such a universal decay indicates a fundamental property of GRBs, reflecting the underlying physics. For instance, it has been argued to be a natural consequence of the relativistically expanding plasma (Pe'er 2008; see, however Deng & Zhang 2014). A full understanding of the physical evolution has yet to lead to predictions that can account for these observations.

Perhaps the most useful and exciting feature of multi-component fitting with a blackbody is the ability to reveal the temporal variation of the properties of the jet such as $r_{ph}$ and $\Gamma$. Several studies have calculated these outflow parameters for different GRBs (Preece et al. 2014; Burgess et al. 2014; Iyyani et al. 2013; Gao & Zhang 2014) and find common trends for both parameters. As shown in Figures 2 and 3, the photospheric radius is seen to monotonically increase with time and $\Gamma$ is observed to decrease with time (see however Gao & Zhang 2014). When combined with the high significance of the detection (see Section 4), a theme begins to form that makes the detection of the blackbody very reasonable.

There are, however; reasons to question fits with a blackbody. On theoretical grounds, the blackbody should not appear with the simple form

$$F_\nu(\epsilon) \propto \epsilon^3 \exp \left( \frac{1}{kT} \right) - 1$$

(1)

used in the above mentioned works. For instance, Pe'er & Ryde (2011) argue that the blackbody should appear as...
broadened or “multi-colored” by geometric and relativistic effects due to the jet shape and high bulk Lorentz factors assumed as properties of GRBs. The fact that pure blackbodies have been observed (Ryde 2004; Ghirlanda, Pescalli & Ghisellini 2013) places serious constraints on the dynamics of the GRB jet as argued by Beloborodov (2011). For example, an unbroadeed blackbody can only be observed if the photosphere occurs during the acceleration phase of the jet while it is photon dominated.

Moreover, the flux of the blackbody compared with the primary non-thermal component also places severe constraints on the dynamics. Daigne & Mochkovitch (2002); Zhang & Yan (2011) argue that introducing magnetization into the outflow allows for some of the total energy of the jet to be entrained in a magnetic field, reducing the available thermal energy. Hence, the intensity of the observed blackbody would be reduced.

These features and issues, being so constraining on the models, require that the existence of the blackbody be confirmed to a high degree to advance the current understanding of GRB outflows. Hence, we investigate the existence of the blackbody in the context of spectral evolution of a single Band component.

3 SPECTRAL EVOLUTION SIMULATIONS

Testing for the false identification of a blackbody due to spectral evolution requires the creation of a set of simulated GRB pulses with known spectral evolution. The Band function, a smoothly broken power law with low and high-energy spectral indices $\alpha$ and $\beta$ respectively ($F(E) \propto E^{\alpha-\beta}$), is the shape of the spectrum to be simulated. This choice is justified by the fact that the Band function is the commonly assumed spectral shape and commonly used to fit the spectrum in both catalog work and routine analysis (Kaneko et al. 2006; Goldstein et al. 2012). A more accurate approach would be to simulate a physical non-thermal emission spectrum from a theoretical model evolving in a physical way in an attempt to see if a blackbody could be reconstructed by mistake from the observations. Due to the lack of knowledge about the emission mechanisms occurring in GRBs, any assumption of a non-thermal model or physical model in general would not be objective. Therefore, the Band function serves an acceptable proxy for a single component emission spectrum.

For simplicity, the spectral evolution that will be simulated is the classic hard-to-soft evolution typically observed in GRBs (Kargatis 1994; Band 1997). The Band function’s $\nu F_\nu$ peak, or $E_\nu$, is evolved in time as a monotonically decreasing power law with decay index $\gamma$ (see Equation 2) while all other parameters except the amplitude are held constant.

$$E_\nu(t) = E_0(t + 1)^{-\gamma}. \quad (2)$$

The evolution of $E_\nu$ is the most pronounced change in the spectra of observed GRBs over their respective durations. To give the simulated pulse a GRB-like flux history, the amplitude is evolved with the KRL pulse shape of Kocevski, Ryde & Liang (2003). With these parameters, the flux and spectrum of the simulated pulses are completely as an evolving, single component GRB pulse.

The method of simulation is described in Burgess (2014). This method affords the ability to map the time evolving photon spectrum into unbinned Fermi Gamma-ray Burst Monitor (GBM) (Meegan et al. 2009) time-tagged event (TTE) data. These data are then fitted using standard techniques. Two values of $\alpha (-1$ and $0$) are selected for each value of $\gamma = 1, 1.5, 2, 2.5$ in the simulations. These values span the typically observed range of $\alpha$ and $\gamma$. With these synthetic GRBs, a control is established because the true spectrum in the simulations is known. We can therefore establish the false-positive of detecting a blackbody in a systematic way.

4 THE TIME-INTEGRATED SPECTRUM

While the presence of the blackbody has been measured in the pre-Fermi era, this work will focus on the fits of Band+blackbody made with the Fermi data. The first such measurement was that of the GRB 100724B (Guiriec et al. 2011) and will serve as an example for our discussion. This GRB exhibited a blackbody in both its time-resolved and time-integrated (fluence) spectra. The measurement of the significance came from the time-integrated spectrum. The spectrum was fit with both Band and Band+blackbody and the C-Stat likelihood statistic (Arnaud et al. 2011) was used to quantify the fit. Because the models are not properly “nested”, the difference in C-Stat ($\Delta$$_{\text{cstat}}$) cannot be used to directly ascertain the significance of adding the blackbody component (Protassov et al. 2002). Therefore simulations were made to obtain the distribution of the $\Delta$$_{\text{cstat}}$ statistic. Essentially, the null hypothesis ($H_0$) is assumed to be a single component Band function. Then several thousand simulations of the fit of only the Band function were generated with a varying background. These simulations were fit with both the Band and Band+blackbody models and the distribution of $\Delta$$_{\text{cstat}}$ was obtained. From this distribution, it was determined that the $\Delta$$_{\text{cstat}}$ from the actual data was at least $5\sigma$, meaning that there is only one chance in 3.5 million that the blackbody component is an artifact of background fluctuations. This does not, however; test if the blackbody arises from spectral evolution of a single component. Therefore, the simulated GRB pulses with spectral evolution are tested here for the presence of an artificial blackbody.
The properties of the integrated fits as a function of $\gamma$ for different values of $\alpha$. The blackbody characteristic energy, $kT$, appears within the range typically observed in the data. The shift in both $E_p$ and $\alpha$ mimic the changes that have been used to justify the presence of a blackbody in the data. These changes should therefore not be used to justify the blackbody or have any physical significance assigned to them.

Using the simulations described in Section 3, the time-integrated spectra of the full set of parameter combinations are fit with both the Band and Band+blackbody model (see Figures 5 and 6). The C-stat values for the fits are recorded and their respective $\Delta_{\text{c-stat}}$ are calculated yielding a tentative estimate of the significance of the addition of the blackbody.

In all cases, a blackbody can be fit in addition to the Band function (see Figure 4).

Moreover, the addition of the blackbody component is statistically significant and modifies the Band function by steepening $\alpha$ and increasing $E_p$ in the same way that has been observed in real data. There is a trend of increasing $kT$ as the speed of the $E_p$ decay (increasing $\gamma$) increases. This is due to the fact that higher values of $E_p$ become rarer in the spectrum when $\gamma$ is large and therefore lower $E_p$ values in the spectra are confused as blackbodies in the

Figure 4. The properties of the integrated fits as a function of $\gamma$ for different values of $\alpha$. The blackbody characteristic energy, $kT$, appears within the range typically observed in the data. The shift in both $E_p$ and $\alpha$ mimic the changes that have been used to justify the presence of a blackbody in the data. These changes should therefore not be used to justify the blackbody or have any physical significance assigned to them.

Figure 5. The $\nu F_\nu$ contour plot of a time integrated fit of the simulated data using the Band function and Band+blackbody. 1σ contours are indicated by the shaded regions. The Band+blackbody model is a significantly better fit and captures the additional curvature below $E_p$.

Figure 6. The convolved count spectrum of the Band function fit (top) and the Band+blackbody fit (bottom). These data are produced via the simulation software described in Burgess (2014).
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5 TIME-RESOLVED SPECTRA

For each simulation, the time-resolved spectra are fit with both the Band and Band+blackbody models and the evolution of $kT$ is computed. The fits are filtered by the improvement of the more complex model over the simpler model via the C-Stat statistic. Figures 8 and 9 show the evolution of $kT$ for various values of $\gamma$ and $\Delta_{cstat}$. There is a clear evolution in $kT$ that is similar to the observations. This would be troubling if the time-resolved blackbodies found in these simulated spectra were statistically significant. However, fitting the more complex model to time-resolved spectra does not improve the fit as significantly as is observed above in the time-integrated spectra. More importantly, many of the blackbodies found in the fits have negative amplitudes which is not physically expected for a photospheric component and suggests the fitting engine is simply using the additional component to smooth over variances in the data. We therefore assign this variation in $kT$ to the fact that $E_p$ is evolving and the blackbody, being a narrow spectral shape, is filling out small, insignificant fluctuations in the spectral data below $E_p$. However, it is not a required component in the spectrum at this time-resolution.

Pushing a bit further, one can use the framework derived in Pe’er et al. (2007) to compute physical jet parameters from the multi-component fits of the simulated data. The values of $r_{ph}$ and $\Gamma$ are computed in Figures 10 and 11 with no significance cuts of the data points. The values of both $\Gamma$ and $r_{ph}$ are similar to what is typically observed in real data, but the trends are not. The trend in $\Gamma$ does have an overall decrease with time which is similar to what is observed in Figure 2 but the behavior is erratic at late times due to the value of $\Gamma$ being dependent of the total flux. Moreover, when cuts on the significance are applied to the data as is done in Figures 8 and 9, there is no longer any trend at all because none of the blackbodies responsible for these calculations are significant. The trend in $r_{ph}$ is completely dissimilar to what is typically observed. The values are sporadic with a slight decrease at late times. The identification of a recurring evolutionary trend for significantly detected blackbodies in real observations therefore points to a physical rather than artificial presence of the blackbody. Several authors have shown that the evolution of the blackbody’s temperature and flux have a common pattern across many GRBs. Theoretical predictions for the overall summed evolution (see Figure 7). Faster evolution also increases the significance of the blackbody detection.

These findings show that using fits of the time-integrated spectrum in order to study the emission process must be done with great caution; the spectral evolution must be accounted for. Moreover, regardless of attempting to detect a blackbody, if the time-resolved spectra are assumed to be Band functions, the integrated spectra can differ significantly from a Band function leading to erroneous conclusions about the spectral shape. In particular, justifying the significance of any additional component, be it a blackbody or a power law, can lead to errors which can not be addressed via statistics. This is particularly a problem for analyzing GRBs that have highly variable lightcurves that cannot be analyzed with time-resolved spectroscopy.

It should be pointed out that it is indeed doubtful that one should find a pure blackbody in the integrated spectra in the first place. Due to the evolution of $kT$ present in the time-resolved spectra Ryde (2004) Axelsson et al. (2012), the integrated spectra would at best contain a multicolored blackbody due to the summing of the evolving spectra. The fact that a blackbody is found in the integrated spectra at all would then suggest that the blackbody component does not evolve in time, which is difficult to consider from a physical standpoint because the luminosity vary strongly in a burst. Therefore, if a blackbody component does exist, the resulting integrated spectrum should be better fit by a Band and multicolored blackbody.

Figure 7. The simulated Band function is plotted from it’s initial, time-resolved shape (purple) until the end of the pulse (light green). The sum of these spectra which would represent the integrated fit is plotted in red. To demonstrate the low-energy broadening effect that spectral evolution introduces, a Band function with parameter values from the actual integrated fit is superimposed on the summed spectra (dashed line). It is this excess flux at low-energy that is responsible for the falsely identified blackbody. It is also clear why including a blackbody component in the time-integrated fit would shift $E_p$ to higher values.

Figure 10. The inferred $\Gamma$ calculated from the falsely identified blackbody component. The overall behavior is not very different from what is observed in the data. However, no cuts on significance have been applied to these data points. Data points that would have been calculated from a blackbody with negative amplitude have been removed.
Figure 8. The evolution of $kT$ for $\alpha = -1$. Fits with a $\Delta_{\text{cstat}} > 5$ are highlighted in red. The blue X’s (see Figure 9) indicate fits where the blackbody amplitude was negative. Therefore the only data points that would survive even a modest significance cut are those that are red without a blue X. Increasing the significance cut to reasonable values eliminates all data points.

Figure 9. The same as Figure 8 but for $\alpha = 0$. 
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6 DISCUSSION

The two component thermal + non-thermal fit of the GRB spectra has become an important focus area in the field because of its power to both constrain emission models and elucidate the structure of the GRB jet. As discussed, it is well established that the addition of the blackbody to spectral fits is statistically significant. The attempt herein has been to verify that the blackbody does not appear in the spectra as an artifact of spectral evolution of single component. We find that in the integrated fit an additional curvature appears that is not accounted for by the Band function alone and it is possible to fit a significant blackbody that is not really there. However, in the time-resolved spectra an extra fit component can not be significantly identified and the results do not match what is commonly found in the actual observations. Therefore, we conclude that the time-resolved (intra-GRB pulse) results of a significant blackbody found previously are likely an observation of a real additional component.

While the spectral evolution simulated in this work does not encompass the variety of evolutions that have been observed, it does model the most commonly observed hard-to-soft evolution. In that respect, one can invoke Occam’s razor and point to the fact that if time-resolved analysis of a GRB with a single component Band function reveals hard-to-soft evolution and then a multi-component analysis reveals a significant blackbody that evolves as the expected way then it is likely the blackbody is not an artifact of spectral evolution. It is entirely possible that more complex spectral evolutions of $E_p$ or even $\alpha$ from a single component can reproduce the evolution of the blackbody observed in the data, but this requires fine tuning.

It remains to be shown that physical simulations of a single component such as synchrotron from internal shocks do not falsely produce a blackbody in a multi-component fit. We note that indeed a single component photosphere emission can produce complex spectra which include a seed Planckian remnant (Pe’er & Waxman 2005; Beloborodov 2010). Without a clear physical model for a single component spectral evolution, it is difficult to test the entire parameter space that could produce an artificial blackbody from single component evolution. Very few GRB models are advanced enough to produce spectrally evolving lightcurves that could be folded through the Fermi instrument response and then fit with the Band+blackbody model as is done in this paper. This test would measure the ability for specific models that do not predict a blackbody to be mistakenly identified as a model that does include a blackbody. For now, this study shows that the standard hard-to-soft evolution observed in GRBs does not produce an artificial blackbody in the time-resolved spectra.

The integrated spectra alone cannot be used to justify the presence of a blackbody (e.g. see Guiriec et al. 2011; Axelsson et al. 2012), but rather the significance of the time-resolved data should be used, which for weak and/or rapidly varying GRBs might be difficult or impossible. As shown above, spectral evolution of a single component Band function can result in a very significant Band+blackbody fit. This further reinforces the point made in Burgess (2014) that time-resolved analysis is crucial to understand the physical properties of GRBs. The integrated properties have no direct mapping into these physical mechanisms. The significance of the blackbody must be evaluated in individual time bins to insure its existence. This also highlights the importance of observed evolutionary trend in multi-component fits. Such an observation is not as easily quantifiable as the statistical significance of an additional component, but it is clearly an important feature to distinguish real (Figure 1) from artificial (Figure 8 and 9) blackbodies.

The goal of this analysis has been to establish the existence of the blackbody in light of the fact that it could arise from spectral evolution. In the end, we have a recipe for eliminating the falsely identified blackbodies. The following elements should be taken into consideration:

- do not use the integrated spectra alone to establish the significance
- the significance of the blackbody should be obtained from the time-resolved spectra
- shifts in $E_p$ and $\alpha$ do not necessarily correspond to evidence of the blackbody or a physical origin such as being more consistent with synchrotron
Figure 12. Band’s $E_p$ from the fits with Band and Band+blackbody for $\alpha = -1$. The evolution is altered near the beginning of the emission for some pulses when a blackbody is included in the model. At late times, the evolution follows the single component fit. Note that these fits are not filtered for significance.

Figure 13. Same as Figure 12 but for $\alpha = 0$. 
the evolution of the outflow parameters should not be erratic and follow the trends already demonstrated in past analysis of significant blackbodies found in time-resolved spectra.

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