Appearances of the Jet Photosphere in GRB Spectra

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There are several strong arguments for considering photospheric emission in GRBs. Here, we describe the two main appearances of the photospheric emission that are currently discussed. In the *multi-component models* the photosphere only contributes to a part of the spectrum, while the main part is due to optically-thin synchrotron emission. In the *photospheric emission models* the whole emission spectrum is from the photosphere: The emission spectrum has been altered due to subphotospheric dissipation and/or off-axis emission. In many cases, though, it is difficult to distinguish between these models on a purely statistical ground. Therefore, more detailed predictions from different physical scenarios should be tested on the observations.

Keywords: GRBs, thermal emission

1. Introduction

Significant progress has been made in our understanding of the prompt emission in gamma-ray bursts (GRBs) over the last 10 years. It is now beyond any reasonable doubt that one has to take into account the emission from the jet photosphere, in order to explain the observed $\gamma-$ray spectra. Indeed, a robust prediction of the fireball model[15 46] is that the relativistic jet is initially opaque. As the flow expands, densities will decrease and the optical depth to Thomson scattering will eventually reach unity and the photons that are entrained in the jet can flow freely to the observer. Photospheric emission, in some form, is thus inevitable[37 23], however, the significance of it in the observed spectrum is not certain. Three important insights lie at the foundation of the recent progress of understanding. (i) the tight correlation between the spectral peak energy and flux within a burst, (ii) the detection of Planck spectra in a few bursts, and (iii) the realisation that the emission from the photosphere in a relativistic outflow is typically not expected to be a Planck spectrum.

(i) The Golenetskii correlation[21] relates the photon energy of the spectral peak to the corresponding energy flux. This is the strongest and most prominent correlation in GRBs and was found only 10 years after the discovery of the bursts themselves. Photospheric emission naturally provides a correlation between these quantities and the correlation (as well as the Amati correlation[3]) has served as an early argument for photospheric emission in GRBs. For instance, Lazzati et al. (2013) performed numerical simulations of GRB jets from unsteady central engines and followed the release of the photospheric emission. They found that the resulting correlation is, indeed, in good agreement with the observed Golenetskii correlation.[32] The Golenetskii correlation has been studied in much detail in many works.[31 9 52 19 33 46 57 26 13 10]

(ii) Using *Compton Gamma-Ray Observatory* BATSE data, Ghirlanda et al. (2003) indentified bursts which, during an initial phase, had spectra which were consistent with a Planck function.[17] In addition, Ryde (2004) found several BATSE bursts which were consistent of having Planck spectra through out their evolution.[48] Reccuring trends of the behaviour of the thermal component were identified, such as the broken powerlaw decay of the temperature.[41 50 53 4 43 18 28 14 44] Later, in Ryde (2005) it was shown that a large fraction of bursts could be fitted by a Planck function in addition to a power law, over the limited energy range of BATSE (20-1800 keV).[49 50] Varying amplitudes of these two components then lead to a broad variation of spectral shapes. Ryde (2005) further argued that this indicates that GRB spectra should be described by a hybrid model, consisting of emission from the photosphere and synchrotron emission from an optically thin region in the outflow, as outlined in Mészáros & Rees (2000).[49 36]

(iii) The typical assumption that is made is that the photosphere in GRBs emits a Planck spectrum (or Wien function in the case of a scatterphere) since the photon distribution should be fully thermalised and the effects of off-axis emission is neglected. However, since the flow is relativistic, several effects could easily alter the spectrum from a Planck function: Energy dissipation at moderate optical depths (subphotospheric dissipation) can cause significant broadening of the thermal component in the flow.[47 40 6 20 8] Moreover, the photosphere is, in general, not expected to be a surface, defined by a single photospheric radius, but rather an extended volume. Variations in the temperature due to expansion[7] as well as high latitude effects on the Lorentz boost of the emission[1] will cause the observer to see a multi temperature emission, significantly broadening the spectrum.[38 34]

Recent analysis of the widths of observed time resolved spectra[4 55] confirm the assertion that the photosphere must play an important role in shaping the spectrum. The width of the νF_ν spectra are found to be too narrow for accommodating a synchrotron component even from the narrowest electron distributions.

These results are consistent with the identification of the line-of-death of GRB spectra[45] which shows that about one third of all measured low-energy spectral-indices (α) are inconsistent with slow-cooling synchrotron emission and nearly all exclude the possibility of fast-cooling synchrotron emission[14]. Hence, both the observed α distribution and the very narrow shapes of the observed spectra put heavy constraints on the applicable synchrotron models to GRBs.

In the following sections we describe two photospheric interpretations of GRB spectra that are currently discussed: multi-component emission and "modified Planck spectra".

2. Multi component spectra

Mészáros & Rees (2000) suggested GRB spectra to consist of multiple emission components, among others, the photosphere and non-thermal emission components from the optically-thin part of the flow.[36] Smearing effects would then lead to the observed spectral shapes. As mentioned above, Ryde (2005) showed that a large fraction of bursts could be fitted with such a scenario, by modelling the BATSE energy range with a Planck function and a power-law[49,51]. The steepness of the power-law component, found in these studies, require an additional spectral break beyond the BATSE energy range (i.e. at > 1 MeV). Based on these arguments Battelino et al. (2007) made predictions for the shape of two-component spectra over the Fermi Gamma-Ray Space Telescope's energy range (8 keV - 40 MeV) including a Planck functions and a synchrotron component. This was later confirmed.[24 12 4 35 25 26 28 14] Multiple spectral breaks in GRB spectra had been claimed even earlier. For instance, using data from the PHEBUS experiment, Barat et al. (1998) found that, apart from the typical spectral break at ~ 300 keV an additional break exists at around 1-2 MeV.[5] Futhermore, Ryde & Pe'er (2009, in their §4.5) found that indeed two spectral breaks could be identified in the couple of bursts for which both BATSE and EGRET data were available with the same temporal resolution.[22 50]

The archetypical burst in this category is GRB110721A[a] which has been modelled by a combination of Band function and a blackbody component[4 11], see figure 1. The value of the peak energy (initially 15 MeV) combined with the α-values excludes the standard optically-thin synchrotron model, only allowing for a slow-cooled synchrotron scenario. Similar conclusions was drawn by Burgess et al. (2014) who used a synchrotron spectrum instead of a Band spectrum in fitting a sample of burst. Only slow cooled synchrotron emission was consistent with the data.[14 30]

Furthermore, in the case of GRB110721A, the time evolutions of Band function peak energy and blackbody temperature show that the thermal component evolve independently from the non-thermal component. This can also be seen by the fact that the second peak in the lightcurve consists only of photons below 100 keV, and is thus associated with a narrow spectral distribution (the blackbody component).[28]

Finally, the photospheric component in GRB110721A allows for the calculation of bulk Lorentz factor of the flow Γ and the position of the flow nozzle measured from the central engine, r_0 (the radius at which the flow starts to accelerate). The trends of these parameters confirm what is seen in other bursts with identifiable thermal components[49 50 42], namely that Γ tends to decrease with time, whereas r_0, increases by more than two orders of magnitude, from 10^6 to $\sim 10^9$ cm during the burst.[28]

Within the multi-component interpretation of burst spectra, it has been argued that a weak or non-existent photospheric component points towards the burst flow to be Poynting-flux dominated. This magnetic flow largely suppresses the thermal component which, in these cases, generally forms less than 10 % of the overall flux.[56 58 25 27 16 59]

[a]The choice is based on the significance of the thermal component and the smoothness of the light curve which allows for unambigious, temporally-resolved spectral analysis to be performed (Burgess & Ryde 2015)

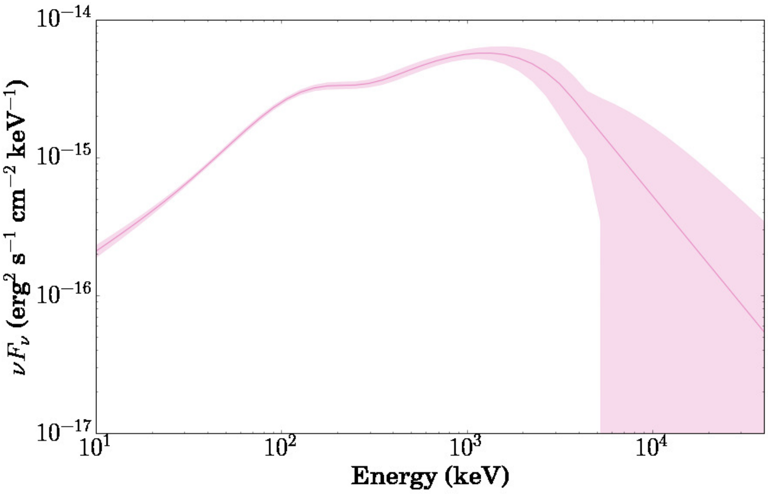

Fig. 1. Time resolved νF_ν spectrum of GRB110721A modeled by a Band function and a blackbody component (see Iyyani et al. 2013) to describe the distinct thermal and non-thermal components in the spectra. The spectral shape obtained corresponds to that of multi component spectra for which the details are given in section 2. Shaded ares are the contours for propagated errors on the flux, which are calculated by taking into account both the errors on total flux of the model and the errors on the flux of the remaining component (see Burgess 2015 for details).

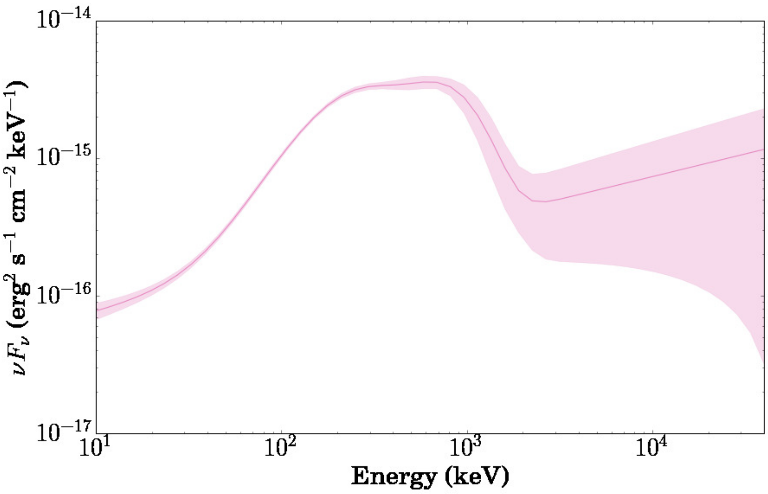

Fig. 2. Same as Fig.1, but for GRB110920A which is modelled by two blackbody components and a power law component (see Iyyani et al. 2015). Such a spectrum is interpreted as a Comptonized spectrum from the GRB photosphere.

3. Photosphere as modified Planck spectra

Energy dissipation at moderate optical depths as well as geometrical effects can cause the emergent photospheric photons to have a distribution that differs significantly from a Planck function. The first observational evidence for such a broadening was given by GRB090902B.[50] In this burst, an initially very narrow spectrum evolved into a broader spectrum. This behaviour was suggested to be explained by subphotospheric dissipation in which the spectrum is mainly shaped by the reprocessing of the initial Planck spectrum by Comptonization. In such an interpretation the emerging spectral shape mainly depends on the physical location of the dissipation, strengths of the dissipation and the magnetic field, as well as the relation between the energy densities of thermal photons and electrons.[54]

Another burst that is best explained by subphotopsheric dissipation is GRB110920A[29], a very luminous burst which makes it an appropriate candidate to study the broadening mechanism. Its spectrum is shown in figure 2, where the spectrum is modelled by two Planck functions and a power-law component. Iyyani et al. (2015) argued that the narrowness and the existence of the two distinct breaks of the time-resolved spectra suggest that dissipation was local at $\tau \approx 20$. Comptonisation of the thermal, soft component gives rise to the two breaks. The ratio of energy breaks largely depend on τ and the ratio r_d/r_s, where r_d is the dissipation radius and r_s is the saturation radius. This, in turn, gives an indication of where the dissipation occurs. The power-law component, on the other hand, is thought to represent the optically thin synchrotron emission forming far above the photospheric radius.

Ahlgren et al. (2015) used a physical subphotospheric dissipation model and fitted it against observed spectra. They simulated the radiation processes by making use of the code described in Pe'er & Waxman (2005). It assumes that photons and particles interact via direct and inverse Compton scattering, pair production/annihilation, synchrotron, and synchrotron self-absorption at the dissipation site below the photosphere. In order to fit to data in XSPEC, Ahlgren et al. (2015) produced a table model of many runs producing DREAM (Dissipation with Radiative Emission as A table Model). Two different bright *Fermi* bursts were selected, GRB 090618 and GRB 100724B. These two bursts have previously been reported to exhibit different shaped spectra. GRB 090618 can be well fitted with a Band function alone and have a single break spectrum. On the other hand, the best fit for GRB 100724B requires the addition of a blackbody component, thus exhibiting double break spectrum. For both of the bursts, DREAM was shown to give a statistically comparable fit to these original spectral fits. The best fit spectra obtained from DREAM are both slightly double peaked, indicating similar physical origin for this two bursts in contrast to original fits. Ahlgren et al. (2015) argue that the difference between the bursts is mainly attributable to the distance between spectral peaks which is in turn directly correlated with the optical depth from which the dissipation takes place.[2 39]

4. Comparison of models

Subphotospheric dissipation, emission from a localized region below the photosphere[53 29 2] and the two-emission-zone model where the thermal and non-thermal components arise in different parts of the flow[49 26 28 14 44], are two main scenarios that are considered to explain the GRB prompt spectra. Although being completely distinct interpretations and predicting different spectral shapes, both of the models are consistent with the data in many cases. As illustrated in Iyyani et al. (2016) (see their figures 10 and 11), a purely statistical approach is often insufficient in distinguishing between the two models for many of the bursts.[30] This situation requires the testing of the physical predictions of each model in itself, after which they can be considered as valid models due to the output from statistical tests.

5. Conclusion

There are several strong arguments for considering photospheric emission in GRBs. First, the strong Golenetskii correlation can naturally be explained by thermal emission.Second, the detection of single Planck function spectra points undeniably to the photosphere. Likewise, the observed spectra are in generally very narrow, which sets strong constraints on non-thermal emission models. Third, the fireball model of GRBs indeed predict a photospheric emission component and, due to the relativistic velocities involved, the emission is only expected to be a Planck function in very specific cases. Typically, the photospheric spectrum should be significanlty broadened.

There are two main appearances of the photospheric emission that are currently discussed. In the *multi-component models* the photosphere only contributes to a part of the spectrum, while the main part is due to optically-thin synchrotron emission. However, the only form of emission that is allowed from observations is that from slow-cooled electrons. This leads to strong constraints on possible physical scenarios. In the *photospheric emission models*, the whole emission spectrum is from the photosphere: The emission spectrum has been altered due to subphotopsheric dissipation and/or off-axis emission. In many cases, though, it is difficult to distinguish between these models on a purely statistical ground. Therefore, more detailed predictions from different physical scenarios should be tested on the observations.

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