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Photospheres in gamma ray bursts: Lessons learned from *Fermi*

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I will summarise the main lessons learned from *Fermi Gamma-ray Space Telescope* observations regarding the behaviour of the photosphere. First, GRB090902B exhibited a clear and distinct component that is best attributed to the jet photosphere. Second, many GRBs have a "double hump" spectrum and a sole Band function cannot model their shapes. Third, *Fermi* confirms *CGRO* BATSE results on thermal emission in GRB pulses, its existence and temporal behaviour. Fourth, *Fermi* provides evidence for sub-photospheric energy dissipation, which can explain the non-thermal spectra seen in many bursts. Indeed, the inclusion of a photospheric emission component is the first step towards an understanding the physical origin of the prompt emission: The Band function does not provide it.

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1. Introduction

In spite of extensive research over the past decades, a complete physical picture of the origin of the prompt GRB emission is still lacking. The failure of the synchrotron interpretation raises the need for alternatives. During recent years, though, evidence has been accumulating that the photosphere of the relativistic outflow in gamma-ray bursts (GRBs) plays an important role in the formation of the observed spectrum (e.g. Ryde et al. 2010, Guiriec et al. 2010, Beloborodov 2010, Lazzati et al. 2011, Giannios 2011, Pe'er et al. 2012). Indeed, a strong contribution from the photosphere was early predicted on physical grounds by Goodman (1986) and Paczyński (1986). However, this was not considered a viable model since the observed spectra are, in general, non-thermal. Moreover, the photospheric emission would be strongly attenuated due to adiabatic losses if the emission occurs at the typically assumed radii. It was, however, realized that the photospheric emission should be accompanied by an optically thin, nonthermal emission (e.g. Mészáros et al. 2002), and that the photospheric emission can be enhanced and modified from a Planck function by energy dissipation at moderate optical depths (Rees & Mészáros 2005 Pe'er et al. 2006).

Below, I summarise what I consider are the main lessons that we have learned from *Fermi* observations regarding the photosphere in GRBs.

2. The photosphere in GRB090902B

Figure 1 shows a time resolved spectrum from the intense burst GRB090902B (Abdo et al., Ryde et al. 2010). The spectrum consists of two components. Apart from the main, peaked

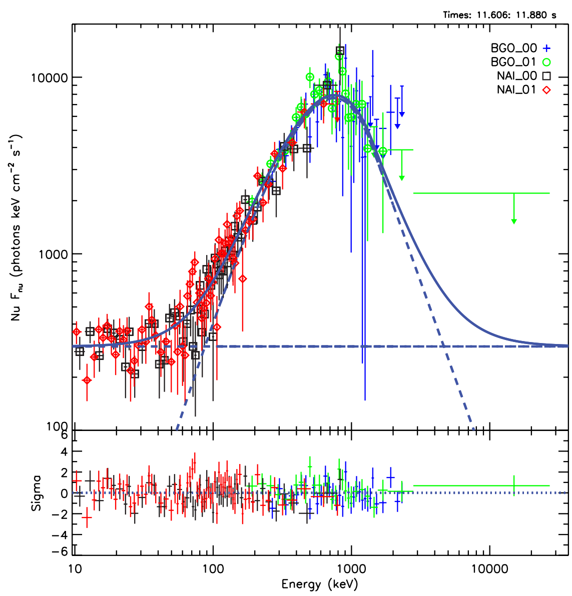

Figure 1: The main spectral component in GRB090902B is close to a Planck function during the initial half of the bursts. The Band function fit shown above is for the time bin $11.60-11.88$ s, and is very narrow with $\alpha = 0.55 \pm 0.16$.

emission component, there is a power law component. The peaked component has two striking features. First, the low energy power law index $\alpha = 0.55 \pm 0.16$, which is among the hardest spectra ever detected (Kaneko et al. 2006). Second, the spectrum is very narrow. The width at half maximum is less than one order of magnitude. These two features may best be explained by emission from the photosphere, having a spectrum slightly broadened from a Planck function. Indeed due to geometrical effects the spectrum from the photosphere is not expected to be a perfect Planck spectrum (e.g., Paczyński 1986).

3. Double Peaked Spectra

The cleanest signature of photospheric emission in GRBs is found in smooth emission pulses, so called FRED (fast rise, exponential decay) pulses (Ford et al. 1993). Ryde (2004) identified a few such pulses in the *Compton Gamma Ray Observatory (CGRO)* BATSE catalogue which were consistent with Planck function spectra throughout their durations, over the observed spectral range 25–2000 keV. This suggested a photospheric origin of the emission. It was further argued in Ryde (2005) that the spectral break in apparently nonthermal spectra can be interpreted as the photospheric emission peak. While the peak is modelled by a blackbody spectrum, an additional power law component is needed to account for the nonthermal character of the spectrum. More importantly, however, the temperature of the blackbody in all pulses is observed to have a characteristic, and recurring, behaviour: It decreases following a broken power law in time. Moreover, the normalisation of the blackbody is also found to exhibit a characteristic behaviour. It increases as a power law in time and is independent of the temperature evolution (see further Ryde & Pe'er 2009). These results reveal that the photosphere in GRBs has a characteristic behaviour.

The *Fermi Gamma-ray Space Telescope* have made further confirmations of this interpretation. It is made clear that for many time resolved spectra the best description is not by a single spectral component, such as the Band et al. (1993) function. Instead, two peaks are present in the spectrum. This can be modelled by adding a blackbody component on the low energy shoulder of the dominating Band function. The low energy peak is described by the blackbody while the high energy peak is described by the Band function. An example is of such a spectrum is GRB100724B, which exhibits a peak due to a blackbody with a temperature of ~ 40 keV, and a peak due to a Band function at ~ 1 MeV (Guiriec et al. 2010). Another example of such a doubled peaked spectrum is GRB110721A, a burst dominated by a single emission episode (Axelsson et al., submitted). Figure 2 shows a time resolved spectrum of this burst. The peak of the Band function decreases as a power law in time and its initial value is a record breaking 15 ± 1.3 MeV (Axelsson et al., submitted). Figure 3 show the evolution of the blackbody component, its temperature and its normalisation. These behaviours are similar to the behaviours found for pulses in *CGRO* BATSE bursts (Ryde & Pe'er 2009): The temperature decays as a broken power law in time, while the normalisation increases like a power law in time. Indeed, if this bursts had been observed by BATSE, the spectrum that would have been detected would be limited to the interval marked by a black line in the figure 2. The spectrum would then have been equally well fitted by a Band function, with an assigned peak value $E_{\rm p} \sim 100$ keV, and by a blackbody + power law model. This is similar to the fits made in Ryde (2005) and in Ryde & Pe'er (2009).

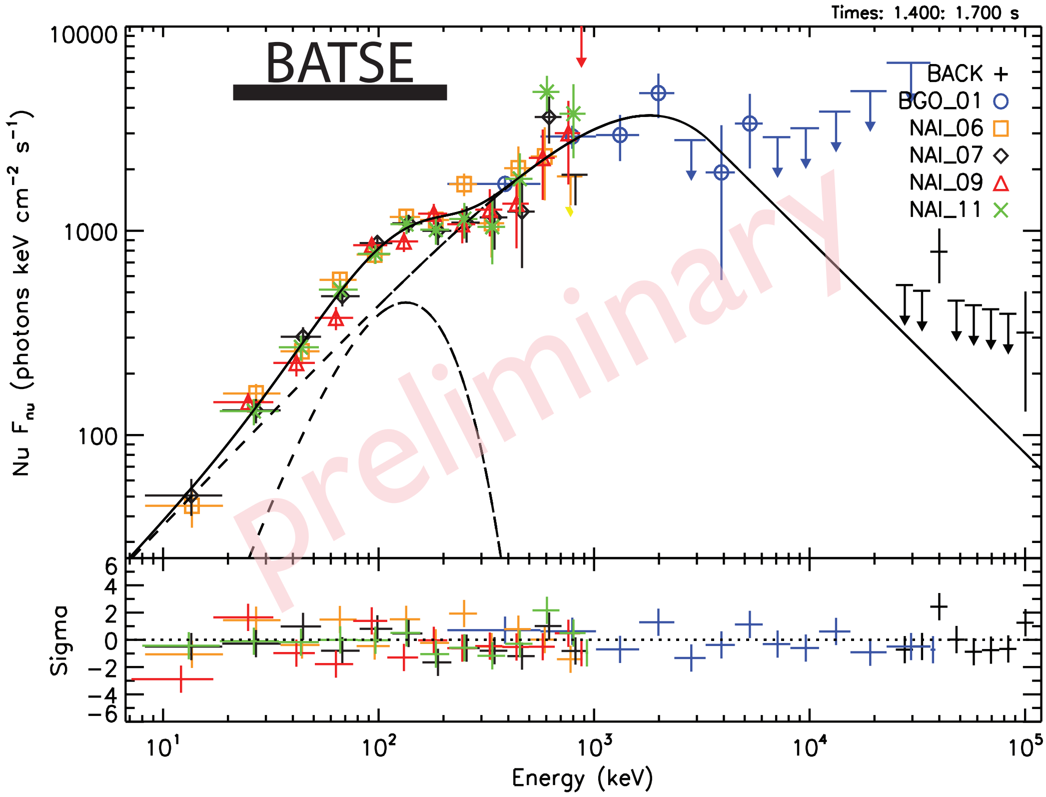

Figure 2: GRB110721A also has a subdominant blackbody component. It is well fit with a 2 component model consisting of a Planck function and a Band function (see Axelsson et al., submitted).

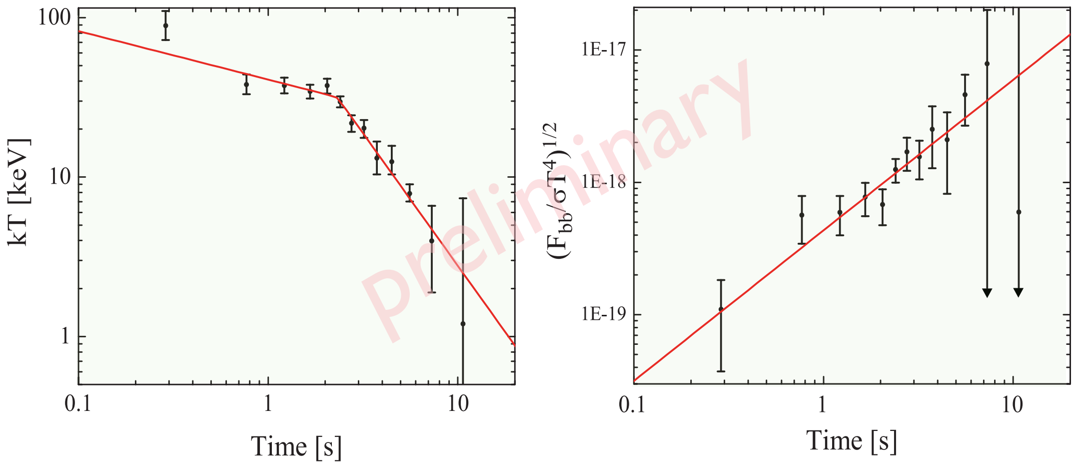

Figure 3: The temperature and the normalisation of the blackbody component follows the well-defined characteristics of the photosphere seen in BATSE bursts (see Axelsson et al., submitted).

4. Spectrum of the photosphere

The bright GRB090902B also provided us with another important piece of information. The main spectral component, which is observed to be very hard and narrow during the initial phase of the burst, is later observed to widen into a broader spectrum. The spectral shape becomes a more typical Band shape, as is frequently observed in other bursts. This implies that the photosphere must be able to have a variety of shapes, not only a blackbody. Such a broadening naturally occurs if energy is dissipated below the photosphere at moderate optical depths (Ryde et al. 2011, Vurm et al. 2011) or due to geometrical effects (Lundman et al. in prep.). The spectrum emerging from the photosphere therefore does not necessarily need to be a blackbody. We point out, however, that for moderate broadening of the spectrum, and in bursts in which the photospheric component is subdominant, a blackbody function is still a good approximation for fitting purposes.

5. Summary

1. The γ-ray spectra of many bursts cannot be modelled by a single Band function. Extra components are needed.
2. The addition of a narrow spectral component (e.g. a blackbody) improves the fit in many cases. This component follows well-defined characteristics.
3. The blackbody component can be dominant or subdominant.
4. The spectrum emerging from the photosphere can be broadened due to subphotopsheric dissipation.
5. The inclusion of the blackbody is the first step towards an understanding the physical origin of the prompt emission: The Band function does not provide it.

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