Thermal Emission in the Prompt Phase of Gamma-ray Bursts

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I discuss the interpretation of the prompt phase in gamma-ray bursts as being dominated by quasi-thermal emission, rather than by synchrotron emission. Such an interpretation gives a more natural explanation of (i) the observed variety of spectral shape and spectral evolution, (ii) the observed narrowness of the distribution of peak energies, as well as (iii) the observed correlations between peak energy and luminosity. However, the physical setting that could produce such a scenario is not yet clear.

1. Introduction

The prompt emission of gamma-ray bursts (GRBs), radiating mainly as gamma-rays and X-rays, has defied any simple explanation, despite the presence of a rich observational material and great theoretical efforts. This is in contrast to the afterglow emission, in many cases detected all the way from X-rays to radio wavelengths, which is successfully described by synchrotron emission from a forward shock moving at great speed into the surrounding medium. Synchrotron emission is also a natural candidate for the prompt emission since it arises naturally in an ultra-relativistic outflow in which the kinetic energy is dissipated through, for instance shocks or magnetic reconnections, and shared between the magnetic field and particles. However, there are several observational facts that contradict such a simple picture, most importantly the existence of spectra which are much too hard, see for instance the spectra from GRB930214 in Figure 1 and GRB960530 in Figure 2. In many cases such spectra are fitted well by a thermal emission function [1–3]. Furthermore, Ryde [4] showed that spectra from more typical bursts, that is, bursts having spectra which are consistent with the synchrotron model, can indeed be fitted with a hybrid model which is dominated by a thermal component, but that is overlayed with a non-thermal emission component as well. In many cases such a model gives a statistically better fit. Such an example is given in Figure 3. Even though bursts appear to have a variety, sometimes complex, spectral evolutions, the behavior of the two separate components is remarkably similar for all bursts, with the temperature describing a broken power-law in time. The non-thermal component is, in most cases, consistent with emission from a population of fast cooling electrons emitting optically-thin synchrotron emission or non-thermal Compton radiation, giving a power-law slope of the photon spectrum of $s = -1.5$. However, in the case of GRB960530, shown in Figure 2, s is closer to $-2/3$, which is expected for slow cooling [5].

It is very important to note that it is the *instantaneous* spectra of GRBs that most closely should reveal the radiation mechanism. This is because of the strong spectral evolution that normally occurs during a burst and that will make the spectral shape of the *time-integrated* spectrum differ from that given by the emission process. This is in particular the case for complex bursts with several emission peaks. The time-integrated spectrum can easily be found from the instantaneous spectra and the spectral evolution, which was shown analytically by Ryde & Svensson [6]; the spectra always become softer.

2. Synchrotron Model

It was early recognized that the spectra of gamma-ray bursts (GRBs) have a non-thermal character, with emission over a broad energy range (e.g. [7]). This typically indicates emission from an optically-thin source and an initial proposal for GRBs was therefore an optically-thin synchrotron model from shock-accelerated, relativistic electrons (e.g. [8, 9]). The number density of the radiating electrons is assumed to be typically a power law as a function of the electron Lorentz factor $\gamma_{\rm e}$ above a minimum value, $\gamma_{\rm min}$, with index $-p$. Such a distribution gives rise to a power-law photon spectrum with photon index $\alpha = -2/3$ below a break energy $E_{\rm p} \propto \gamma_{\rm min}^2$ and a high-energy power-law with index $\beta = -(p+1)/2$. However, as mentioned above, this model has difficulties in explaining the observed spectra of GRBs, which show a great variation in α and β (see [10]). In particular, a substantial fraction of them have $\alpha > -2/3$, which is not possible in the model in its simplest form, since $\alpha = -2/3$ is the power-law slope of the fundamental synchrotron function for electrons with an isotropic distribution of pitch angles [11]. The problem becomes even more severe for the case when the cooling time of the electrons is shorter than the typical dynamic timescale. In the typical setting of GRBs having a relativistic outflow with a bulk Lorentz factor $\Gamma \sim 100$, the time scales for synchrotron and inverse Compton losses are $\sim 10^{-6}$ s [12], which is much shorter than both the dynamic time scale $R/2\Gamma^2 c \sim 1$ s $(R/10^{15}$ cm), and the integration time-

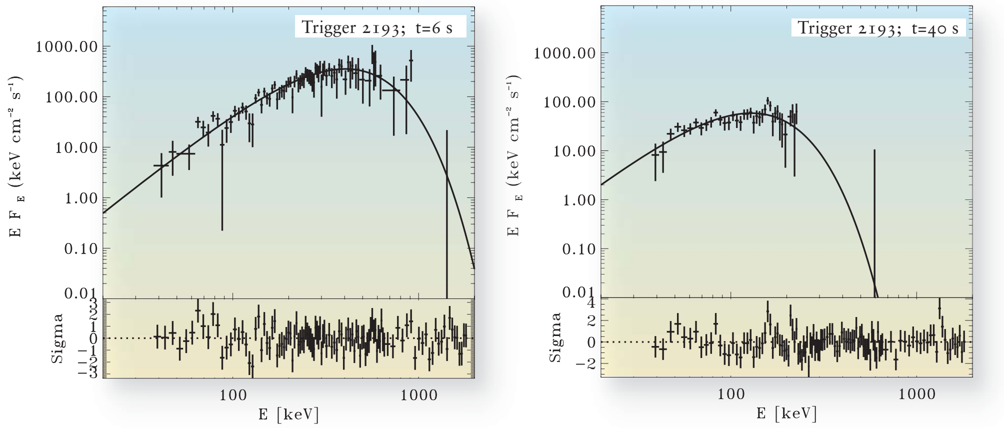

Figure 1: Two time-resolved spectra from GRB930214 (BATSE trigger 2193) from 6 and 40 seconds after the trigger. Note that the spectra are fitted well with a Planck function, both in the Rayleigh-Jeans portion of the spectrum with $\alpha = +1$ and in the Wien portion with a fast voidance of flux. The temperature has changed between the measurements.

scale of the recorded data, typically 64 ms to 1 s. In such a case the low-energy power-law should be even softer, with $\alpha = -1.5$ [13, 14], now contradicting a majority of the observed spectra. Furthermore, the observed distribution of α from *instantaneous* spectra is smooth (see [10]) and does not show any indication of preferred values, such as $-2/3$ or $-3/2$. Other variations of the synchrotron or/and inverse Compton model have been suggested (see e.g. [15–17]) to account for these hard spectra.

The peak energy from the above distribution of electrons is given by $E_{\rm pk} = \gamma_{\rm m}^2 B_\perp \Gamma$. In the external shock model $\gamma_{\rm m}$ and $B_\perp$ are proportional to the bulk Lorentz factor, which makes $E_{\rm pk} \propto \Gamma^4$, which is a very strong dependence, which poses a problem in explaining the relative narrowness of the distribution of peak energies [10], even including the X-ray flashes. For the internal shock model the $\gamma_{\rm m} \propto \Gamma_{\rm rel}$, which is the relative Lorentz factor between the two shells that collide and

$$E_{\rm pk} \propto B_\perp \Gamma. \tag{1}$$

However, the sharing of the energy between the kinetic energy of the electrons and the magnetic fields should lead to a larger dispersion.

A third complication arises in explaining the observed correlation between peak energy and the luminosity which was discussed by Lloyd-Ronning et al. [18] and Amati et al. [19] (see also [20]); the peak energy is correlated with the isotropically equivalent energy given by

$$E_{\rm pk} \sim \left(\frac{E_{\rm iso}}{1.2 \times 10^{53} \rm erg}\right)^{0.40 \pm 0.05} \tag{2}$$

where $E_{\rm iso}$ is

$$E_\gamma = (1 - \cos\theta) E_{\rm iso} \tag{3}$$

where E_γ is the actual gamma-ray energy emitted and θ is the jet opening half-angle of the collimated outflow.

Equation (1) shows that in the internal shock model $E_{\rm pk}$ is proportional to the Lorentz boosted magnetic field strength. The total energy density

$$U = \frac{(B\Gamma)^2}{8\pi} \propto \frac{L}{R^2} \tag{4}$$

The typical radius for the internal shocks to occur is $R_{\rm sh} \sim c t_{\rm v} \Gamma^2$, where $t_{\rm v}$ is the typical variability time scale, and thus

$$E_{\rm pk} \propto \Gamma^{-2} L^{1/2} t_{\rm v}^{-1}. \tag{5}$$

To get a relation similar to that in equation (2) both Γ and $t_{\rm v}$ have to be quite similar for all bursts, which is difficult to imagine. Even though there is no direct way of determining the bulk Lorentz factor, various physical models give suggestions on plausible relations between the luminosity and the bulk Lorentz factor. For instance, [21] argued for $L \propto \Gamma^2$. Such a relation would thus give $E_{\rm pk} \propto L^{-1/2}$, that is, an anti-correlation, in contradiction to the observed behavior (see also [22, 23]). Additional assumptions are needed to explain the positive correlation. Invoking Poynting flux and/or pair dominated models the correlation also becomes positive [23].

3. Quasi-thermal models

If the prompt phase is indeed dominated by a thermal component these three issues become natural consequences. First, as shown by Ryde (2004, 2005) the relative strength and the slope of the non-thermal component will determine the value of the low-energy

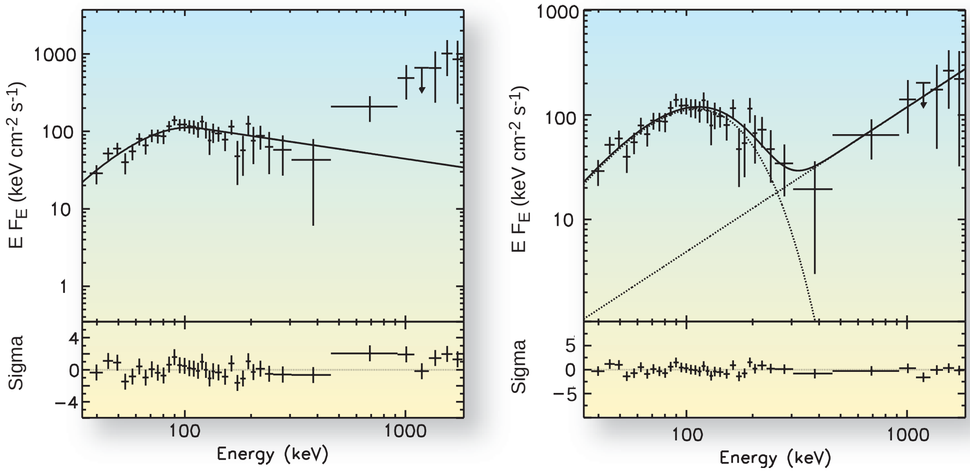

Figure 2: The same spectrum from GRB960530 (#5478; 6 s after the trigger) fitted with (left panel) the Band et al. [24] model with $\alpha = 1.7 \pm 1.5$ and $\beta = -2.4 \pm 0.3$ and (right panel) the hybrid model [3], with a power-law slope of $s = -0.62 \pm 0.27$. Note the obliging of the data points [**?**].

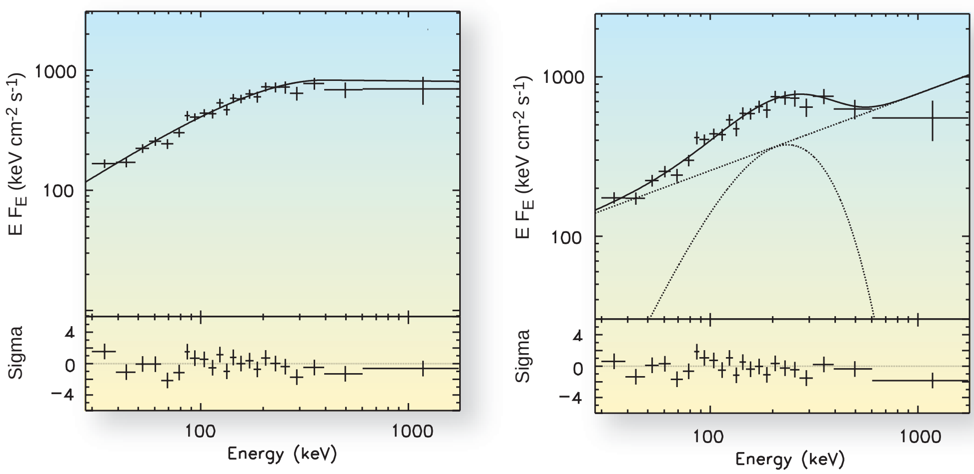

Figure 3: The same spectrum from GRB911031 (#973; 2.5 s after the trigger) fitted with (left panel) the Band et al. [24] model with $\alpha = -0.86 \pm 0.12$ and $\beta = -2.4 \pm 0.3$ and (right panel) the hybrid model [3], with a power-law slope of $s = -1.52 \pm 0.04$.

power-law index, α, that would be found if the Band et al. [24] function were to be used. If the thermal component is strong and/or the non-thermal component is hard, the resulting spectrum will have a hard α (see Fig.2). While if the non-thermal component becomes relatively stronger and/or softer the measured α-value would be softer (see Fig. 3). The observed distribution of α-values is therefore consistent with this picture and in particular the spectra beyond the "line-of-death" [25] are not conspicuous. A strong spectral evolution, for instance, in a large change in the measured value of α, is also easily explained.

Second, the peak of the spectrum is now determined of kT and is less sensitive to the bulk Lorentz factor. In fact, if the photosphere occurs during the acceleration phase it is practically independent of Γ. Rees & Mészáros [26] suggest a model where the photospheric emission can become enhanced by dissipative effects below the photosphere (magnetic reconnections, shocks) and subsequent Comptonization, see also [27]. Typical values for the peak energy would be hundreds of keV.

Third, the correlation in equation (2) has a natural explanation since for a thermal emitter the luminosity and the temperature are correlated. For instance, equating $E_{\rm pk}$ with the energy density, one gets $E_{\rm pk} \propto \Gamma kT \propto \Gamma U^{1/4} \propto \Gamma(L/\Gamma R^2)^{1/4}$. Using that the pair photosphere occurs at $R_{\rm ph} \propto L\Gamma^{-3}$ (see Rees & Mészáros [26]) then $E_{\rm pk} \propto L^{\sim 0.8}$. In the last step, $L \propto \Gamma^2$ was again assumed. Similarly if the photosphere is emitted during the acceleration phase its temperature will be constant in the observer frame since the comoving cooling by adiabatic expansion is compensated for by the increase in Γ.

$$\Gamma k T_0 \propto \left(\frac{L}{R_0^2}\right)^{1/4} \propto L^{1/4} R_0^{-1/2}. \qquad (6)$$

Here, R_0 is the radius at which the linear acceleration starts. Assuming, for instance, that $R_0 \propto L^{-1}$ then again $E_{\rm pk} \propto L^{0.75}$ (see further Rees & Mészáros [26]). Finally, for extremely photon starved plasmas $E_{\rm pk} \propto L/N_\gamma \propto L$.

4. Conclusions

The radiative efficiency of the thermal emission can in plausible scenarios be radically increased by, for instance, dissipation processes below the photosphere [26, 27]. These processes would naturally produce large amount of electron-positron pairs with modest Lorentz factors, which would Compton up-scatter the thermal radiation. The observed peak would then be this Comptonized peak. The non-thermal emission seen in the spectra, could be due to synchrotron emission or inverse Compton emission from dissipation regions outside the photosphere. Ryde [4] showed that the energy flux in the thermal and the non-thermal components are correlated which might indicate the latter.

In summary, thermal emission could indeed dominate over non-thermal emission in standard settings of a GRB jet. In such scenarios a correlation between the peak energy and the luminosity naturally arises, the details somewhat depending on the dissipation processes. In addition, the dispersion in $E_{\rm pk}$ would be smaller and the observed spectral shapes and spectral evolution get natural explanations.

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