Thermal Emission from Gamma-Ray Bursts

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Abstract. In recent years, there are increasing evidence for a thermal emission component that accompanies the overall non-thermal spectra of the prompt emission phase in GRBs. Both the temperature and flux of the thermal emission show a well defined temporal behaviour, a broken power law in time. The temperature is nearly constant during the first few seconds, afterwards it decays with power law index $\alpha \sim 0.7$. The thermal flux also decays at late times as a power law with index $\beta \sim 2.1$. This behaviour is very ubiquitous, and was observed in a sample currently containing 32 BATSE bursts. These results are naturally explained by considering emission from the photosphere. The photosphere of a relativistically expanding plasma wind strongly depends on the angle to the line of sight, $\theta$. As a result, thermal emission can be seen after tens of seconds. By introducing probability density function $P(r, \theta)$ of a thermal photon to escape the plasma at radius $r$ and angle $\theta$, the late time behaviour of the flux can be reproduced analytically. During the propagation below the photosphere, thermal photons lose energy as a result of the slight misalignment of the scattering electrons velocity vectors, which leads to photon comoving energy decay $\epsilon'(r) \propto r^{-2/3}$. This in turn can explain the decay of the temperature observed at late times. Finally, I show that understanding the thermal emission is essential in understanding the high energy, non-thermal spectra. Moreover, thermal emission can be used to directly measure the Lorentz factor of the flow and the initial jet radius.

Keywords: gamma rays:bursts — plasmas — radiation mechanism:non-thermal — radiation mechanism:thermal — scattering

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INTRODUCTION

It is widely believed that the prompt emission from GRBs arise from the prompt dissipation of a substantial fraction of the bulk kinetic energy of a relativistic outflow, originating from a central compact object. The dissipated energy is converted to energetic electrons which produce high energy photons by synchrotron and synchrotron self Compton (SSC) scattering. This interpretation was found to be consistent with a large number of GRB observations [1, 2], which generally show a broken power law spectrum at the keV – MeV energy range (which has became known as the “Band function” [3, 4, 5, 6]).

In spite of its many successes, in recent years there are increasing evidence for low energy spectral slopes that are too steep to account for by the optically thin synchrotron - SSC model [7, 8, 9]. Motivated by these findings, an additional thermal (blackbody) component was suggested that may contribute to the observed spectrum [7, 8, 9]. Indeed, from a theoretical point of view, such a component is inevitable: the optical depth near the base of the flow is enormous, $\tau_e \gtrsim 10^{15}$ (for a review, see, e.g., [14]), thus photons emitted by the inner engine that produces the burst, or by any dissipation mechanism that occurs deep enough in the flow, necessarily thermalize before decoupling the plasma at the photosphere. While in principle these photons are the first to reach the observer (if emitted on the line of sight), in practice, due to the Lorentz contraction the observed time difference between thermal photons originating from the photosphere and non-thermal photons originating from dissipation above the photosphere can be shorter than millisecond, and thus not be resolved. It should be stressed here, that due to the multiple dissipation processes episodes expected during the prompt emission (e.g., by internal shock waves), the existence of thermal photons do not contradict emission of non-thermal photons, but adds to it.

The interpretation of the prompt emission as being composed of thermal emission component in addition to the non-thermal one, was put forward by Ryde [15]. In this work, analysis of the time-resolved spectra of nine bright, long GRBs which were characterized by hard low energy spectral slopes, showed that a dominant thermal component could be used to explain the observed spectra. It was found in this work that the temperature of the thermal component is approximately constant and equals a canonical value of $T^{\text{th}} \approx 100\text{keV}$ for a few seconds, afterwards it decays as a power law in time with power law index $\alpha \simeq 0.6 \sim 1.1$. Ryde suggested later on [16] that a thermal component could in fact exist in many bursts in which it does not necessarily dominate over the non-thermal component.

The suggestion made by Ryde, combined with the theoretical arguments mentioned above, had motivated further
FIGURE 1. Left: an example of spectral modeling using a thermal + a single power law to model the non-thermal spectrum. Example is shown for BATSE trigger 1974 (GRB921003). Middle and right: temporal evolution of the temperature (middle) and flux (right) of the thermal component. The temperature is nearly constant for $\sim 1.5$ s, afterwards it decreases as a power law in time. The flux also shows a broken power law temporal behaviour, with a break time which is within the errors of the break time in the temperature evolution. Results are shown for BATSE trigger 3765 (GRB950818). Very similar results are obtained for a large sample of bursts (see text).

work on the origin of the prompt emission, and the role played by the thermal photons. The results of this work are published in a series of papers [17, 18, 19], in which various aspects of the problem are examined. Here, I summarize the main results found so far. I first present the key results of the work by Ryde & Pe’er [17], which provide, for the first time, a full analysis (flux and temperature) of the temporal behaviour of the thermal emission component observed in a large (32) sample of GRBs. I then present a theoretical interpretation, based on the analysis done in [18]. Finally, I argue that thermal emission, in addition to its contribution (via Compton scattering) to the high-energy, non-thermal spectrum, can be used to deduce important physical parameters of the flow, such as the Lorentz factor, $\Gamma$ and the initial jet radius.

EVIDENCE FOR THERMAL EMISSION: REPETITIVE BEHAVIOUR

We use the method developed by Ryde [15, 16], to model the prompt emission spectra in the BATSE detector range (20 keV − 2 MeV) as being composed of a thermal component and a single power law. While being incomplete in nature, this model, which contains four free parameters (similar to the number of free parameters in the “Band” model) provides good statistical fits ($\chi^2$/d.o.f. $\simeq 1$) to the spectra in the BATSE range. An example of this fit is presented in figure 1 (left).

Key results were found when we used this method to model time resolved spectra. In a sub-sample of $\approx 300$ long BATSE bursts, the spectral and temporal coverages are good enough to enable splitting of the lightcurves into separate time bins and model the spectra in each time bin (typically of duration $\sim 1/2$ s) separately. The first important result is that so far, we were able to identify a thermal emission component, and to model the time resolved spectra in the way described above in all the cases studied (currently, our sample contains 32 bursts, in which the thermal component does not necessarily dominate the spectrum). By doing so, we retrieved the results found by Ryde [15] (using a smaller sample) about the well-defined temporal behaviour of the temperature of the thermal component (see fig. 1 middle): the temperature is typically found to be nearly constant for a few seconds, afterwards it decay as a power law in time with power law index $\alpha \approx 0.4 − 0.9$.

We continued further to analyse the temporal behaviour of the flux of the thermal component (see fig. 1 right).

1 A single power law cannot be used to model the data at energies far above or far below the limited BATSE range; nonetheless, theoretically a single power law for the non-thermal emission can be justified over a limited energy range. See discussion below.

2 Temperature and flux of the thermal component, power law index and normalization of the single power law component.

3 This research is still on-going.

4 Typically, minimum thermal flux of $\sim 10 − 20\%$ of the total flux is needed to be able to identify the thermal component.
FIGURE 2. Histograms of the power law indices of the late time decay of the temperature (left) and the thermal flux (right) in a sample of 32 bursts. In all the cases, not only we were able to identify a thermal component, but the temporal behaviour of both the temperature and flux show a broken power law behaviour, with very similar indices for the different bursts at late times.

Here, too, we found a well defined temporal behaviour: the thermal flux slightly rises for a few seconds, afterwards it decays as a power law in time with power law index $\beta \simeq 2.1$. In all the cases studied, the break time in the flux is within the errors of the break time in the temperature. The most important result is the repetitive behaviour of both the temperature and the flux of the thermal component: a similar temporal behaviour (broken power law of both the temperature and thermal flux) was found in all the cases studied so far, with very similar power law indices. Histograms of the late time power law indices for the sample of 32 bursts are presented in figure 2.

THEORETICAL MODEL AND EXPECTATIONS

Our basic assumption in an attempt to understand these results is that thermal photons originate either from the inner engine that produces the relativistic outflow, or from an unspecified dissipation process that occurs deep enough in the flow, so that the photons thermalize before escaping the plasma at the photosphere. The angular dependence of the photospheric radius in a relativistically expanding plasma, characterized by constant Lorentz factor $\Gamma$ and constant mass ejection rate was first studied by [20]. Recently, we showed [18] that it can be formulated in a surprisingly simple form,

$$r_{ph}(\theta; \Gamma) = \frac{R_d}{\pi} \left[ \frac{\theta}{\sin(\theta)} - \beta \right] \approx \frac{R_d}{2\pi} \left( \frac{1}{\Gamma^2 + \frac{\theta^2}{3}} \right). \quad (1)$$

This function is plotted in figure 3 (left) for two values of $\Gamma$. Here, $R_d$ is a constant which depends on the mass ejection rate, $\theta$ is the angle to the line of sight, $\beta$ is the plasma expansion velocity and the last equality holds for $\theta \ll 1, \Gamma \gg 1$. The strong $\theta$-dependence implies that for characteristic GRB luminosity $L = 10^{52}\text{L}_\text{erg s}^{-1}$ and $\Gamma = 10^2 \Gamma_2$, thermal photons escaping the photosphere from high angles to the line of sight $\theta \approx 0.1 \theta_{-1}$ (estimated GRB jet opening angle; see, e.g., [21]), are delayed with respect to photons originating on the line of sight by $\approx 30 \Gamma_2^{1/2} \theta_{-1}^{3/2} \text{s}$.

The definition of a photosphere as a surface in space from which the optical depth to scattering equals unity, is however, incomplete: photons have a finite probability of being scattered at every point in space in which electrons exist. Therefore, in order to fully quantify the last scattering event positions, one needs to use probability density function $P(r, \theta)$. Using the simplified assumptions that the last scattering event radius is independent on the scattering angle, and that in the (local) comoving frame the scattering is isotropic, we showed [18] that the probability density function can be written as

$$P(r, \theta) = \left( \frac{R_0}{r} \right) \frac{e^{-(r_0/r)}}{2\Gamma^2 \beta [1 - \cos(\theta)]^2}, \quad (2)$$

5 A possible alternative model is emission of thermal radiation by dissipation above the photosphere.
Carlo simulation shows the positions of the last scattering events of photons originating from below the photosphere. The green line shows $r_{ph}(\Gamma = 100)$, which by definition is the surface in space from which the optical depth $\tau_{ph} = 1$. Contour lines are added to show the distribution of the last scattering events positions. Clearly, last scattering events positions are located (with different probabilities) in the entire space, while $r_{ph}$ as defined here only gives a first approximation.

The probability density function enables an analytic calculation of the late time decay of the flux and energy of the thermal photons originating from below the photosphere. In the calculation, we use the diffusion approximation, in which all the photons are injected into the flow at the center of the expansion, at time $t = 0$ (i.e., $\delta$-function injected in space and time). The photons are coupled to the flow until the last scattering event takes place. Therefore, before decoupling, the velocity component of the photons in the direction of the flow is $\alpha \approx \beta c$. The observed time delay of a photon whos last scattering event is at $(r, \theta)$ with respect to a "trigger" photon that was emitted at the center of the flow at $t = 0$ and was not scattered at all, is thus $t^{ob} = \Delta t^{ob} = (r/\beta c)[1 - \beta \cos(\theta)]$. The observed flux is calculated by integrating the probability of a photon to be scattered over the entire space, while maintaining the correct arrival time, $F^{ob}(t^{ob}) \propto \int dr \int d\theta P(r, \theta) \delta \left(t^{ob} = (r/\beta c)[1 - \beta \cos(\theta)] \right)$. At late times, this gives $F^{ob}(t^{ob}) \propto t^{ob-2}$ (see figure 4 left).

The observed energy of a photon is blue shifted by the Doppler factor $\mathcal{D}(\theta) \equiv \Gamma(1 - \beta \cos(\theta))^{-1}$ with respect to its (local) comoving energy, which itself depends on the photon propagation radius within the flow, $\epsilon' = \epsilon'(r)$, via two effects: the first is adiabatic energy losses of the scattering electrons. The second is energy loss of the photon due to the slight misalignment of the scattering electrons velocity vectors. Thus, even if there is no energy exchange between an electron and a photon in a single scattering event (i.e., Thompson scattering), the next scatterer’s velocity vector is not parallel to the first ones, hence the photons’ energy in the frame of the next scatterer is slightly lower. We showed in [18], that deep inside the flow this effect leads to photon (local) comoving energy loss, $\epsilon'(r) \propto r^{-2/3}$, which relaxes as the photon approaches the photospheric radius $r_0$ to $\epsilon'(r; r \gtrsim r_0) \propto r^{\alpha}$. Using again the probability density function defined in equation 4 the temporal evolution of the observed energy of photons originating from below the photosphere is obtained by an integration over the entire space in a similar way to the calculation of the flux, $\epsilon^{ob}(t^{ob}) \propto \int dr \int d\theta P(r, \theta) \epsilon'(r) \mathcal{D}(\theta) \delta \left(t^{ob} = (r/\beta c)[1 - \beta \cos(\theta)] \right)$. At late times, this gives $\epsilon^{ob}(t^{ob}) \propto t^{ob-\alpha}$, with $\alpha \approx 1/2 - 2/3$. The analytical results, together with the more accurate numerical results are plotted in figure 4 (middle).

The theoretical model thus gives well-defined predictions for the late time thermal flux and temperature decay: provided that the inner engine decays fast enough, the observed flux of thermal photons is expected to decay as $r^{-2}$, and the observed temperature as $r^{-\alpha}$ with $\alpha \approx 1/2 - 2/3$. The characteristic time scale of the decay is predicted to

$\tau^{ob} \approx \frac{R_d}{2\pi^2}$. In order to validate the approximations used, as well as the assumptions of the diffusion model presented below, we carried a Monte Carlo simulation that traces the photons from deep inside the flow until the final scattering event. The results of this simulation are presented in figure 3 (right).

In the analysis presented we treated single photons, while a temperature is defined for Plank distribution of photons. Although the observed spectrum deviates from Planck spectrum, being a convolution of Planck spectra it is not expected to deviate much from it.

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6 This effect is very similar to energy loss by adiabatic expansion of the photons. Note though that the conditions here are somewhat different than that of classical adiabatic expansion, since the photon propagation volume is in principle not limited.

7 In the analysis presented we treated single photons, while a temperature is defined for Plank distribution of photons. Although the observed spectrum deviates from Planck spectrum, being a convolution of Planck spectra it is not expected to deviate much from it.
Observed flux [arb. units]

FIGURE 4. Left: observed thermal flux as a function of the observed time, presented in units of normalized time, \( t_N \equiv r_0(1 - \beta)/c \). The blue (solid) line is the numerical simulation result, and the red (dash) line is the analytical approximation. Clearly, the analytical approximation is good at late times, where the thermal flux decays as \( F^{\text{obs}} (t^{\text{obs}}) \propto t^{\text{obs} - \alpha} \). Middle: same for the observed temperature. At late times, the simulation results and the analytical model predict observed temperature decay \( T^{\text{obs}} (t^{\text{obs}}) \propto t^{\text{obs} - \alpha} \), with \( \alpha \approx 1/2 - 2/3 \). Right: examples of time averaged spectra obtained for different values of the optical depth \( \tau_p \) at the dissipation radius, under the assumption that thermal component exists. \( \tau_p = 1 \) represents dissipation at the photospheric radius, \( r_0 \). The electrons energy distribution is modified by multiple Compton scattering with the thermal photons, and as a result the spectrum deviates from a broken power law typical for optically thin synchrotron- SSC emission. See [23, 24] for details.

be tens of seconds.

IMPLICATIONS: COMPTON SCATTERING AND PROPERTIES OF THE FLOW

The existence of thermal emission component is potentially crucial in understanding not only the spectrum in the BATSE range, but the very high energy (> MeV) spectra as well. Thermal photons can serve as seed photons for Compton scattering by energetic electrons produced by dissipation processes in the flow [13, 22, 23, 24]. Since the nature of the dissipation processes (e.g., internal shock waves or magnetic reconnection) is yet unclear, it may occur at a variety of radii, including near or below the photosphere. In this case, energy exchange via both inverse and direct Compton scattering with the thermal photons may significantly modify the electrons energy distribution, and as a consequence a variety of non-thermal spectra, which cannot be described by a simple broken power law may be obtained [23, 24]. The effect on the high energy spectra may be significant even if the dissipation occurs at radii which are 1-2 orders of magnitude above the photosphere. Examples of possible spectra are plotted in figure 4 (right).

In addition to their role as seed photons for Compton scattering, thermal photons can be used to directly probe the properties of the flow. The theoretical model presented above is able to explain the late time temporal decay of both the temperature and the flux of the thermal emission. If this explanation is correct, it implies that the thermal photons observed at early times (before the temporal break) are emitted on the line of sight. The dimensionless ratio of the thermal flux and temperature \( R \equiv (F^{\text{obs}} / \sigma T^{\text{obs}})^{1/2} \), where \( \sigma \) is Stefan’s constant, is thus proportional to \( r_0 / \Gamma d_L \), where \( d_L \) is the luminosity distance, and the Lorentz factor \( \Gamma \) originates from relativistic aberration. For constant flow velocity, \( r_0 = r_{ph} (\theta = 0) \propto L / \Gamma^3 \) (e.g., [23]), where the luminosity \( L \) can be determined once the flux and the redshift are known. Thus, both the Lorentz factor \( \Gamma \propto (L / R d_L)^{1/4} \) and the photospheric radius \( r_0 \) can be directly determined for bursts with known redshift and identifiable thermal component.

In principle, \( r_0 \) is the innermost radius from which information can reach the observer. However, the fireball model predicts the dynamics of the plasma below the photosphere using energy and entropy conservation (e.g., [23]). Using these assumptions, we showed [19] that the base of the jet \( \gamma \propto d_L R \), and thus can be determined. Using this method for GRB970828 at redshift \( z = 0.96 \) we found \( \Gamma = 305 \pm 28 \) and \( r_{\text{base}} = (2.9 \pm 1.8) \times 10^8 \) cm. These results are consistent with earlier estimates, based on light crossing time arguments and early afterglow emission measurements. Former methods, though, can provide either lower limit or values estimates good to an order of magnitude, while the

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8 Defined here as the radius at which \( \Gamma = 1 \); \( r_{\text{base}} \) may also be identified with the sonic point.
statistical error in the method presented here on the value of \( \Gamma \) is \( \simeq 10\% \).

**SUMMARY**

In this work we examine various aspects of thermal emission from GRBs. Ryde & Pe’er \[17\] use the method suggested by Ryde \[15, 16\] to analyze the prompt emission spectra in an alternative way to the commonly used broken power law (the “Band” model). By doing so, we introduce a new physical meaning to the spectrum, as being composed of thermal + non-thermal emission. We find a repetitive behavior of both the temperature and the thermal flux, in a sample of 32 bursts. The late time decay indices of the temperature and flux are consistent with the predictions of the theoretical model developed by Pe’er \[18\], based on the idea of extended photospheric emission from higher angles and higher radii\[19\]. We showed that thermal emission must be considered in order to correctly interpret emission at higher energies (at the GLAST energy band). Moreover, we showed \[19\] that thermal emission can be used to determine important parameters of the GRB outflow, such as the Lorentz factor and the radius at the base of the jet.

We find the repetitive behaviour and the agreement between the theory and observations very encouraging. We continue our work on this project, as we believe that it could provide new understanding of the mechanism and physics of the prompt emission and of GRB progenitors.

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9 Systematic uncertainty due to the unknown non-thermal flux also exists; this though can in principle be removed using late time measurements.
10 This idea has some similarities to the “high latitude emission” models used to model GRB afterglow emission. However, here we treat emission from optically thick rather than optically thin plasmas.