Observations, theory and implications of thermal emission from gamma-ray bursts

A. PE’ER\(^1\) and F. RYDE\(^2\)

\(^1\) Space Telescope Science Institute, Baltimore, MD 21218, USA; Riccardo Giacconi Fellow.
\(^2\) Department of Physics, Royal Institute of Technology, AlbaNova, SE-106 91 Stockholm, Sweden

Abstract

Recent analyses show evidence for a thermal emission component that accompanies the non-thermal emission during the prompt phase of GRBs. First, we show the evidence for the existence of this component; Second, we show that this component is naturally explained by considering emission from the photosphere, taking into account high latitude emission from optically thick relativistically expanding plasma. We show that the thermal flux is expected to decay at late times as \(F_{\text{BB}} \sim t^{-2}\), and the observed temperature as \(T \sim t^{-\alpha}\), with \(\alpha \approx 1/2 - 2/3\). These theoretical predictions are in very good agreement with the observations. Finally, we discuss three implications of this interpretation: (a) The relation between thermal emission and high energy, non-thermal spectra observed by Fermi. (b) We show how thermal emission can be used to directly measure the Lorentz factor of the flow and the initial radius of the jet. (c) We show how the lack of detection of the thermal component can be used to constrain the composition of GRB jets.

1 Introduction

Despite many efforts, a clear understanding of the physical origin of the photons observed during the prompt emission phase in GRBs is still lacking. The prompt emission spectra are often fitted with a broken power law
model (known as the “Band” function, [1]). However, recent Fermi-LAT results show that this fit is inadequate in some cases in which high energy photons are observed (e.g., [2]). Even more importantly, the “Band” function fit does not, by itself, carry any explanation about the physical origin of the observed photons. A common interpretation is that the peak observed at sub-Mev range is due to synchrotron emission [3]. However, while the synchrotron interpretation is consistent with many afterglow observations, this interpretation is inconsistent with the majority of the prompt spectra, due to steep low energy spectral slopes observed [4].

This inconsistency motivated us to search for an alternative explanation. Arguably, the most natural ingredient is a thermal component, that should exist in the outflow. In principle, thermal photons can originate either by the initial explosion, or by any dissipation of the kinetic energy that occurs deep enough in the flow, in region where the optical depth is $\gg 1$, so that the emitted photons thermalize before escaping the plasma.

In a series of papers [5, 6, 7, 8, 9, 10, 11, 12, 13] we have extensively studied the contribution of a thermal emission component to the overall (non-thermal) GRB prompt spectra. Our research is focused on both the observational properties [5, 6, 11, 13], theoretical modeling [7, 8, 10] and implications of the existence of this component [9, 12]. We give here a brief summary of our key results.

## 2 Observational clues

Two main difficulties exist in interpreting the observed spectrum. The first is that clearly, in addition to the thermal component there is a strong non-thermal part. The second is that the properties of the thermal component, (temperature and flux) may be time-dependent, hence its signal is smeared in a time-integrated analysis, as is frequently done. In order to overcome the second problem, one needs to carry a time-dependent analysis. Such an analysis was indeed carried by Ryde (5, 6). In these works, a hybrid model (thermal + a single broken power law) was found to adequately describe the prompt spectra of 9 burst over the limited BATSE energy band. Moreover, the temperature of the thermal component showed a repetitive behaviour: a broken power law in time, with power law index $T(t) \propto t^{-2/3}$ after the break time at few seconds.

Repeating a similar analysis on a larger sample of 56 bursts, we found (11) that the same repetitive behaviour is ubiquitous. Moreover, in this work we also considered the evolution of the thermal flux, and found that it
too shows a similar behavior: a broken power law, with index $F(t) \propto t^{-2}$ at late times. The break time, not surprisingly, is the same within the errors to the break time found in the temperature behaviour. Histograms of the late time power law indices are shown in figure 1.

3 Theoretical interpretation

As thermal photons originate from below the photosphere, one needs to study the properties of the photosphere in a relativistically expanding plasma. In such a plasma, Lorentz aberration plays a significant role: for example, the photospheric radius strongly depends on the angle to the line of sight, $\theta$, via $r_{ph}(\theta) \propto (\theta^2/3 + \Gamma^{-2})$, where $\Gamma$ is the factor Lorentz of the outflow [10]. This strong dependence implies that photons emitted from the photosphere at high angles are significantly delayed with respect to photons emitted on the line of sight: $\Delta t^{ob} \approx 30L_{52}^{1.2} \theta_1^4 \Gamma_{-2}^{1.2} \text{ s}$, where $L$ is the GRB luminosity and $Q_x = Q/10^x$ in cgs units is used.

Calculations of the expected decay of the flux and temperature at late times are carried under the assumption that the source (the inner engine) terminates abruptly at a given time. Photons emitted off axis are delayed ("high latitude" emission in optically thick expanding plasma), resulting in flux decay at late times. Moreover, due to both weaker Doppler boosting and energy losses to the expanding plasma at large radii, these photons’ observed temperature is also lower. By integrating over equal arrival time surface in the entire space, it was shown ([10]) that the flux decays at late times as $F(t) \propto t^{-2}$ and the temperature as $T(t) \propto t^{-\alpha}$, with $\alpha \approx 1/2 - 2/3$. 

Figure 1: (Left, center): Histograms of the late time decay indices of the temperature (left) and thermal flux (center) in a sample of 56 bursts (taken from [11]). Right: theoretical results of the flux decay at late times, showing $F(t) \propto t^{-2}$ (taken from [10])
The results of the theoretical calculations of the flux decay (both numerical and analytic) are shown in figure 1 (right).

Clearly, the theoretical predictions are in excellent agreement with the observations. While this by itself does not prove that indeed the photons that we see are thermal, we find the agreement between theory and observations, as well as the repetitive behaviour seen, two very strong, independent indications that we indeed are able to properly identify the thermal emission component and discriminate it from the non-thermal part.

4 Implications

The existence of a thermal emission component, which, as described, is a natural outcome of the fireball model, can bring a breakthrough in our understanding of the physics of GRB prompt emission. We discuss here three important implications of it.

The relation between thermal and non-thermal emission. As GRB prompt spectra is non-thermal, clearly, in addition to any thermal component there is a non-thermal part. Thus, according to our picture, the observed spectrum is composed of (at least) two separated ingredients, thermal component originating from the photosphere, and non-thermal component originating from the kinetic energy dissipation above the photosphere. The true properties of this non-thermal part can only be deduced after subtracting the contribution from the thermal part. This, however, is not an easy task: since thermal photons serve as seed photons to Compton scattering by energetic electrons (produced by the dissipation mechanism above the photosphere), they contribute to the cooling of these electrons. Hence, the resulting non-thermal spectrum (from, e.g., synchrotron emission or Compton scattering) depends not only on the properties of the acceleration mechanism (e.g., the power law) but also on the relative contribution of the thermal photons. This can lead to a variety of very complex spectra (see [7] [8]), which depend on the various parameters - the photospheric radius, the dissipation radius, magnetic field strength, etc. Interestingly, we were able to show that for a relatively large parameter space region, a single power law may be sufficient to model the non-thermal part over a limited energy range. This result is indeed consistent with the single-power law fitting of the non-thermal part of the spectrum seen in several recent Fermi bursts (e.g., GRB090902B, [2])

Measuring the parameters of the outflow. One major advantage of identifying the thermal emission, is that its radius of origin is known
- it is the photosphere. The ratio of the thermal flux and temperature, \( \mathcal{R} \equiv (F/\sigma T^4)^{1/2} \) (\( \sigma \) is Stefan’s constant) must therefore be proportional to the photospheric radius (for photons emitted on the line of sight). In fact, due to Lorentz aberration, we showed (\cite{9}) that \( \mathcal{R} \propto r_{\text{ph}}(\theta = 0)/\Gamma \).

In the classical “fireball” model, the photospheric radius depends only on two parameters: the (kinetic) luminosity, and the Lorentz factor. Hence, for bursts with known redshift, one can use the three measurable quantities of emission at the photosphere (thermal flux, temperature and GRB distance) to deduce the values of the three unknowns - the luminosity, the Lorentz factor and the photospheric radius itself. Moreover, in the classical fireball model, the dynamics below the photosphere is fully determined by the conservation of energy and entropy. One can therefore use the values of the luminosity and Lorentz factor at the photospheric radius to deduce the radius at which the initial acceleration began. This radius is denoted here as \( r_0 \). Implementing these ideas, we were able to show that for GRB970828, at redshift \( z=0.96 \), the terminal Lorentz factor is \( \Gamma = 305 \pm 28 \), and \( r_0 = (2.9 \pm 1.8) \times 10^8 \) cm. The statistical errors in the estimate of the Lorentz factor, \( \pm 10\% \) are by far the smallest from all the methods known today.

Deducing the outflow composition. GRBs show a wide variety of properties from burst to burst. While in some bursts, thermal emission component is very pronounced (e.g., in GRB090902B the low energy spectrum is so steep and the peak is so narrow that it is very difficult to find an alternative explanation to the peak; see \cite{13} ), in other bursts it is much less pronounced. As one example, in the bright burst GRB080916C, the “Band” model provides a good fit to the spectrum, up to the highest observed photons energies, at 13.2 GeV \cite{14}. Opacity arguments can easily show that these energetic photons cannot originate from the photosphere, but from some (significantly) larger radius \( R_\gamma \sim 10^{15} \) cm. The lack of the detection of a thermal component as predicted by the baryonic models strongly suggests that a significant fraction of the outflow energy is initially not in the “fireball” form. Thus, we found \cite{12} the most plausible alternative to be Poynting flux entrained with the baryonic matter. The ratio between the Poynting and the baryonic flux in this burst is at least \( \sim (15 - 20) \).

\footnote{Note that there is an uncertainty in estimating the kinetic luminosity from the flux. This uncertainty can be removed once afterglow measurements are available.}

\footnote{Note that opacity argument by itself does not give the emission radius; in order to obtain that, one needs to specify the relation between the radius and the Lorentz factor. The results often used in the literature, \( r = \Gamma^2 c \delta t \) rely on assumed knowledge of the variability time \( \delta t \), which is highly uncertain.}
5 Summary

The existence of a thermal emission component, which, as described, is a natural outcome of the fireball model, has a potential to bring about a breakthrough in our understanding of the physics of GRB prompt emission. It is therefore the subject of an extensive on-going research, from all aspects. We stress, that the different physical environment prevents using the tools developed for studying the afterglow in the study of the prompt emission.

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References

[1] Band, D. et al., Astrophys. J., 413 (1993) 281.
[2] Abdo, A.A. et al. (the Fermi collaboration), Astrophys. J. Lett., 706 (2009) L138.
[3] Frontera, F. et al., Astrophys. J. Supp., 127 (2000) 59.
[4] Preece, R.D. et al., Astrophys. J., 506 (1998) L23.
[5] Ryde, F., Astrophys. J., 614 (2004) 827.
[6] Ryde, F., Astrophys. J. Lett., 625 (2005) L95.
[7] Pe’er, A., Mészáros, P., & Rees, M.J., Astrophys. J., 635 (2005) 476.
[8] Pe’er, A., Mészáros, P., & Rees, M.J., Astrophys. J., 642 (2006) 995.
[9] Pe’er, A., Ryde, F., Wijers, R.A.M.J., Mészáros, P., & Rees, M.J., Astrophys. J. Lett., 664 (2007) L1.
[10] Pe’er, A., Astrophys. J., 682 (2008) 463.
[11] Ryde, F., & Pe’er, A., Astrophys. J., 702 (2009) 1211.
[12] Zhang, B., & Pe’er, A., Astrophys. J. Lett., 700 (2009) L65.
[13] Ryde, F. et al., Astrophys. J. Lett., 709 (2010) L172.
[14] Abdo, A.A., et al. (the Fermi collaboration), Science, 323, (2009) 1688