Photospheric emission in gamma-ray bursts

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A major breakthrough in our understanding of gamma-ray bursts (GRB) prompt emission physics occurred in the last few years, with the realization that a thermal component accompanies the over-all nonthermal prompt spectra. This thermal part is important by itself, as it provides direct probe of the physics in the innermost outflow regions. It further has an indirect importance, as a source of seed photons for inverse-Compton scattering, thereby it contributes to the nonthermal part as well. In this short review, we highlight some key recent developments. Observationally, although so far it was clearly identified only in a minority of bursts, there is indirect evidence that a thermal component exists in a very large fraction of GRBs, possibly close to 100%. Theoretically, the existence of a thermal component has a large number of implications as a probe of underlying GRB physics. Some surprising implications include its use as a probe of the jet dynamics, geometry and magnetization.

Keywords: Gamma-rays bursts; hydrodynamics; radiation mechanism: nonthermal; radiation mechanism: thermal.

1. Introduction

Our understanding of gamma-ray bursts (GRB) prompt emission has been revolutionized in the past few years. This is thanks to new observatories, in particular the *Swift* and *Fermi* satellites, new methods of data analysis, and new theoretical ideas of interpreting these results. As a result of these progresses, we think that it is fair to claim that we reached a point in time where we are witnessing a "paradigm shift" in our understanding of this phenomena. A major part of this paradigm shift is attributed to the realization that a thermal component exists in a large fraction of GRBs, and the realization of its importance as providing a new tool to study the underlying GRB physics.

This rapid progress in this field manifests itself in a large number of excellent reviews that were written in the last few years. A partial list of reviews that were published only in the last five years include reviews by Refs. 1–10. This short review is not aimed at competing with any of the above, but rather to highlight one aspect of the progress, which we find of particular importance: that of thermal emission component that is observed during the prompt phase of many GRBs. There are currently good reasons to believe that such a component in fact exists in many GRBs in which it is not directly observed, the reason for this being its distortion by various processes. As we will discuss here, this component, whether independently as well as in combination with other, nonthermal parts of the spectra, provides a wealth of novel ways of interpreting and understanding the data. It can be used to study the underlying physical properties of GRB outflows, such as the jet geometry or jet magnetization, that do not seem, at first sight, to be related to thermal emission. As a consequence, it may very well hold the key to a more complete understanding of the underlying physics of the chain of events that eventually results in the production of a GRB.

We begin this review by a short historical overview in Sec. 2. We then discuss the current observational status in Sec. 3, and present theoretical ideas in Sec. 4. We summarize and conclude in Sec. 5.

2. Historical Overview

Interestingly, the very first works in which it was realized that GRBs are of cosmological origin, proposed that the emission should be (quasi)-thermal.[11–16] This idea originates from the realization that the huge amount of energy, $\gtrsim 10^{53}$ erg released in a small volume, of typical size $r \sim 10^7 - 10^8$ cm (that is deduced from light crossing time arguments and the rapid, $\gtrsim$ ms variability observed) must result in an extremely high optical depth to scattering by particles in the plasma. The rapid interactions between the energetic photons and particles/low energy photons (in producing pairs) lead to the formation of a "fireball", similar in nature to the early evolution of the expanding universe.[17] In this regime of optical depth $\tau \gg 1$, all emerging radiation must be thermal. The observed spectrum, though, was predicted to be somewhat distorted from a pure "Planck" function, due to light aberration effects in the relativistically expanding winds (see Ref. 11).

These ideas could be tested in the early 1990's, following the launch of the *Compton gamma ray observatory* (CGRO) in 1991 that led to the accumulation of detailed spectral data. Contrary to the initial expectations, CGRO spectral data was found to be inconsistent with the initial predictions. Data accumulated mainly by the BATSE instrument on board the CGRO showed clearly that the observed spectral shape of the vast majority of GRBs do not resemble a "Planck" function. Rather, the (time integrated) spectra could be easily fitted with a nearly featureless broken power law spectra, which peaks at the sub-MeV energy range. This to became known as the "Band" function (after the late David Band; see Refs. 18–22).

The leading theoretical interpretation of this nonthermal spectra was, and still is, synchrotron emission by relativistic electrons.[23–30] This is a very common mechanism that is capable of explaining nonthermal emission in many different astronomical objects, from solar flares to active galaxies. As such, it is well studied since the 1960's (e.g. Ref. 31), and its basic theoretical framework appears in many textbooks (e.g. Ref. 32). Further support of this idea came from the fact that synchrotron emission fits very well GRB afterglow emission (at least during late-times; see Ref. 33 onward). The synchrotron emission (presumably peaking at the sub-MeV range to match the prompt emission data) is expected to be accompanied by inverse-Compton scattering at higher energies (synchrotron self-Compton (SSC)). Alternative models suggested that energetic protons may have a substantial contribution to the spectra via proton-synchrotron emission or photo-pair production (see Refs. 34 and 28). The hadronic models, though typically require the deposition of a very large amount of kinetic energy, due to the much less efficient emission from protons as compared to electrons.

Although the synchrotron emission model became widely accepted by the mid 1990's, already in the late 1990's evidence began to accumulate that the low energy spectral slopes (below the sub-MeV peak) observed in the vast majority of GRBs are steeper than allowed by the synchrotron or synchrotron-SSC models.[35–38] A second difficulty is the inability of this model to explain the observed correlation between peak energy and luminosity (Refs. 39 and 40) without invoking additional assumptions (Refs. 41 and 42).

From a theoretical perspective, the synchrotron model relies on the existence of energetic particles and strong magnetic fields. Within the context of the internal shock model, particles gain their energy following internal shocks that dissipate the outflow kinetic energy. However, a well known problem is the very low efficiency in energy conversion, typically no more than a few %.[43–50] A second theoretical problem that arises from fitting the data is that the required values of the magnetic field needed to explain the observed sub-MeV peak are close to equipartition, while fits of the afterglow data show that the magnetic fields produced at shock fronts are typically two orders of magnitude below equipartition, and in many cases less.[33,51] A third problem is the fact that the energy of the peak is very sensitive to the model parameters (bulk Lorentz factor, Γ, electron's temperature, θ_e and magnetic field, B): $E_{\rm peak} \propto \Gamma \theta_e^2 B$. Given the large differences among the various GRBs, it is difficult to explain the observed narrow clustering of the peak energy without fine tuning the model's free parameters.

These observational and theoretical drawbacks of the purely nonthermal emission models have led to renewed interest in thermal models.[52–59] A key difference between these new thermal models and earlier models is the realization that a thermal component is not the sole emission component, and is in most cases accompanied by a nonthermal component. One difference between the different theoretical ideas is the relative strength of the thermal versus nonthermal parts of the overall nonthermal spectra. Within the framework of the basic "fireball" model, such differences are explained by the different photospheric radii: during the coasting phase, the photons suffer a substantial adiabatic losses, and both the temperature and the thermal luminosity drop as $\propto r^{-2/3}$. As the photospheric radius is uncertain, weak thermal signal can be explained as originating from large photospheric radius.

In many of these hybrid models, the observed sub-MeV peak was thought to originate from the thermal component, while the nonthermal part acts to broaden the "Planck" spectra. These assumptions enabled these models to overcome many of the drawbacks of the pure thermal and pure nonthermal models. In particular:

(1) the existence of hard low energy spectral slopes; (2) temporal variations in the spectral shape; (3) the observed spectral correlations between the peak energy and luminosity; (4) the high efficiency (thermal photons originate directly from the explosion, and as such no kinetic or magnetic energy dissipation is needed in producing them); and (5) they naturally explain the existence of a complex spectral shape.

Despite these successes, these models were, by and large, heuristic in nature. For example, the thermal and nonthermal parts were treated as completely separate entities. Another example is that temporal evolution was not treated in a quantitative way. In fact, a major breakthrough took place when it was realized (Refs. 60 and 61) that one needs to look at *time-resolved* spectra. As the emission mechanisms vary with time, time-integrated spectra can easily smear out any signal. Clearly, this produces a much larger technical challenge. In many GRBs (certainly in the BATSE era), there were simply not enough photons observed to enable spectral analysis on short times. Still, there were several bright GRBs for which such an analysis could be done.

3. Observational Status

A key point which is particularly confusing to many people, is the fact that one needs to discriminate between direct and indirect evidence for the existence of a thermal component. A direct evidence for a thermal component — namely, a direct observation of black body, or grey body spectra in GRBs is relatively rare. Furthermore, in most cases in which it is observed, it is accompanied by a nonthermal part. Nonetheless, the fraction of GRBs in which a pure thermal component is observed increases with (1) the GRB brightness; and (2) when time resolved spectroscopy is performed. These two facts strongly point towards the possibility that in many bursts this component is simply smeared, due to the low number of photons detected: nearly by definition, the flux of most bursts observed is close to the detector's limit, and thus only very few photons are observed for most GRBs reported. Combined with the fact that both the thermal and nonthermal parts of the spectra vary with time, it is clear why direct observations of a thermal component are difficult and rare.

As opposed to this, indirect evidence for the existence of a thermal component exist in a very large fraction of bursts. These evidence are based mainly on fitting the low energy spectral slopes (below the peak energy) in "Band" model fits. The theory of synchrotron radiation provides a robust upper limit on the low energy spectral slope that can be observed: $F_\nu \propto \nu^{-\alpha}$, with $\alpha \geq 1/2$ (in the "fast cooling" regime).[32,62,63] This upper limit, though, is lower than the spectral slopes observed in the majority of GRBs.[35–38] This result implies that the (simple version) of the synchrotron model by itself cannot explain the spectra. This motivated several authors to suggest modifications to the model, by altering one or more of its underlying assumptions. Suggestions include addition of a spatial scale for the decay of this field (Refs. 64–67), modify the acceleration process (Refs. 68 and 69) or substantial modification of the low energy particle distribution due to inverse-Compton scattering (Ref. 70). When such modifications are made, much better fits to the spectra can be made.[71]

Nonetheless, recent works suggested an even more robust way of testing the synchrotron prediction, by looking at the spectral width of the entire spectrum (rather than focusing on the low energy spectral slope). The results of these works (Refs. 72 and 73), in fact, suggest that a thermal emission component exists in nearly 100% of all GRBs.

3.1. *Direct evidence*

The most robust way of claiming the detection of a thermal component is by fitting the spectra — or part of the spectra, with a "Planck" (or modified Planck) function. This provides a direct probe of (1) the thermal flux, and (2) the temperature of the thermal component. However, unfortunately, as is stated above, this is often not an easy task.

There are two reasons for this difficulty, and both are related to the analysis method. First, for most GRBs the spectral analysis is based on analyzing flux integrated over the entire duration of the prompt emission, namely the spectra is time-integrated. Clearly, this is a trade off, as enough photons need to be collected in order to analyze the spectra. For weak bursts, this is the only thing one can do. However, obviously this inevitably leads to smearing of any time-dependent signal, and produces artifacts.[74]

Second, the analysis is done by a forward folding method, which implies the following: a model spectrum is convolved with the detector response, and compared to the detected counts spectrum. The model parameters are varied in search for the minimal difference between model and data; this gives the best fitted model's parameters. However, this method implies that the outcome of the analysis is biased by the initial hypothesis: as the fitted results depend on the model that was initially chosen, two different models can provide equally good fits to the same data.

A particular source of difficulty is the wide-spread use of the "Band" model in fitting the prompt emission spectra. Having only four free parameters, fitting the data using this model is unable to capture any "wiggles" or "bumps" that may exist in the spectra. But existence of such wiggles are exactly the indicators for a possible thermal component atop a nonthermal spectrum! In particular, a composite spectra, in which a thermal component is only one ingredient would be completely smeared. This is the key reason why study of a thermal component in GRBs was delayed for over a decade.

In order to overcome both problems, a different analysis method was suggested by Ryde (Refs. 60 and 61). First, fits to the prompt emission spectra were carried using a "hybrid" model, that contains a thermal component (a "Planck" function) in addition to a single power law (see Fig. 1). The rational was to keep the number of free parameters to four (same as in the "Band" model), for ease of comparison

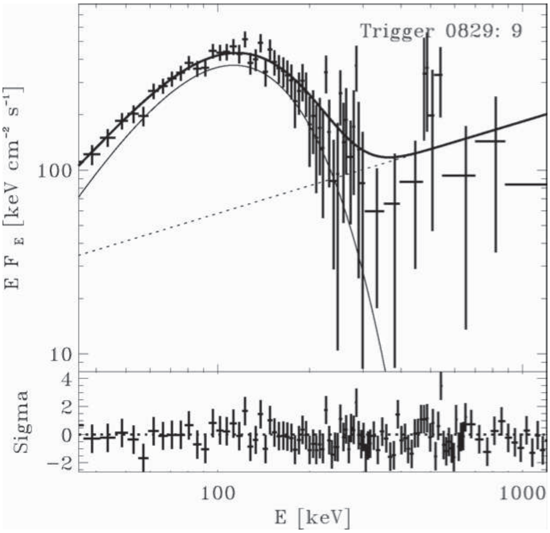
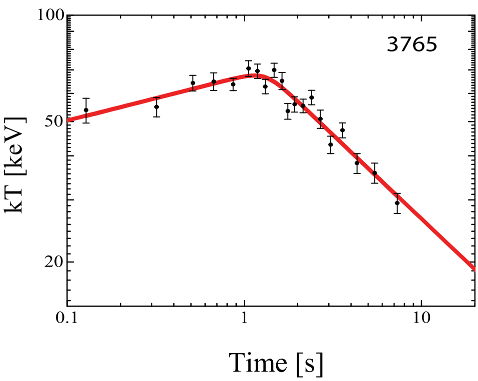
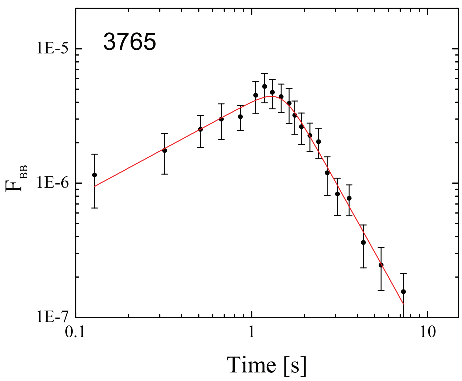


Fig. 1. A "hybrid" model fit to the spectra of GRB 910927 detected by BATSE.

of quality of fits. On the downside, clearly a single power law cannot represent any physical emission process; it can, though, be acceptable over a limited energy range, as was available during the BATSE era. A second novelty was the use of time resolved spectral analysis. While this limited the number of bursts in which the analysis could be carried to only $\mathcal{O}(10)$, it enabled, for the first time, the detection of a temporal evolution of the properties of the xthermal component (see Fig. 2).



(a)



(b)

Fig. 2. Temporal evolution of the temperature (left) and flux (right) of the thermal component of GRB950818. The temperature is nearly constant for ~ 1.5 s, afterwards it decreases as a power law in time. The flux also shows a broken power law temporal behavior, with a break time which is within the errors of the break time in the temperature evolution.

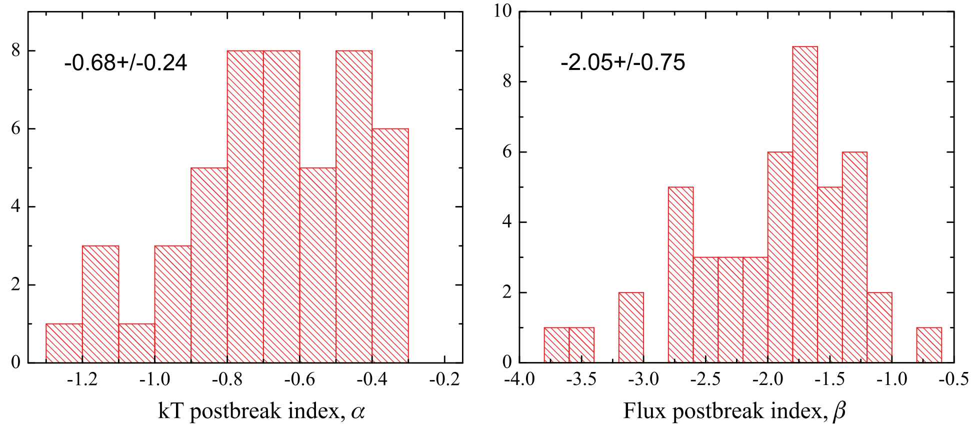


Fig. 3. Histogram of the late-time (after the break) temporal evolution of the temperature (left) and flux (right) in the sample of 56 GRBs from Ref. 75.

This analysis was extended by Ref. 75, to study the properties of 56 BATSE GRBs, the largest sample at that date. That analysis revealed a clear repetitive behavior in the properties of the thermal component, which were found to be distinctive from those of the nonthermal part. The temporal evolution of both the temperature and thermal flux show a well-defined, broken power law behavior. The temperature was found to be nearly constant at $t \leq t_{\rm brk} \sim$few s, and then decayed as $T(t) \propto t^{-\alpha}$, with $\langle\alpha\rangle = 0.68$. The thermal flux first rise as $F(t) \propto t^{\beta}$ with $\langle\beta\rangle = 0.63$, and after break time (which typically coincide with the break time observed in the evolution of the temperature) it decays with an average index $\langle\beta\rangle = -2$ (Fig. 3). This repetitive temporal behavior serves as an independent indicator for the existence of a distinct thermal component; for the least, a component that is distinct from the nonthermal part of the spectrum in both its spectral and temporal properties (see discussion on the theoretical interpretation below).

The launch of *Fermi gamma-ray space telescope* in 2008, enabled much broader spectral range than was available prior to its launch. The increase in spectral range made it clear that in many GRBs a simple four component "Band" function is insufficient to describe the broad band spectrum. Contrary to some initial expectations (Ref. 76), it was found that in many GRBs the prompt spectra can only be fitted with multiple spectral components, that contain several "wiggles". In some basic sense, this is of no surprise, as the "fireball" model was constructed to enable multiple emission zones with different physical conditions. There is thus no *a priori* reason to believe that all emission zones will produce identical spectra. This conclusion is further strengthen by *Fermi's* detection of a typical delay of few seconds in observations of the high energy photons (e.g. Refs. 77–80).

Despite this progress, still in the *Fermi* era, it is found that the "Band" function provides reasonable fits to the vast majority of GRBs.[81–86] Many of these fits differ than earlier fits by the use of time-resolved analysis. Still, as explained above, in these fits "Band" model template was *a priori* assumed, implying that "wiggles" could not be detected. Thus, these fits cannot exclude the possibility that a thermal component does exist, and could be revealed if more sophisticated templates were in use. Furthermore, it is found that the deviations from the "Band" fits are more likely to occur in bright GRBs (Ref. 87), emphasizing the important of sufficient photon number statistics in drawing conclusions about GRB spectral properties. Nonetheless, these analyses imply that in most GRBs the observed spectrum is, by and large, nonthermal and the thermal component, if indeed exists, is not dominant — it is always accompanied by a nonthermal part.

An exceptional burst was the very bright burst GRB090902B (see Refs. 77, 88 and 89). Its spectra showed an extremely bright thermal component, well distinct from the nonthermal part (see Fig. 4). The thermal component was so pronounced, that the spectra rejected any attempt to be fitted with a "Band" model, despite numerous efforts. Attempts to fit only the thermal part with a "Band" model concluded that both the low and high energy slopes are so steep that only a "Planck" spectrum could provide a physical origin to the fit. Furthermore, being so bright, it was easy to follow the temporal evolution of the prompt emission. After a few seconds, the thermal component began to spread, resembling more and more a "standard" "Band" function.[89]

While GRB090902B was a single event, its appearance clearly demonstrated the fact that multiple spectral components indeed exist in the prompt emission spectra. Furthermore, their relative strength can vary during the prompt phase. These findings encouraged several authors to abandon the "Band" fits and search for thermal emission, by modifying the *a priori* assumed template. Indeed, once more complicated templates began to be used, a thermal component (on top of a nonthermal spectra) was found in several bursts. A few notable examples are GRB090510 (Ref. 78), GRB090618 (Refs. 90 and 91), GRB110721A (Refs. 92 and 93), GRB100724B (Ref. 94), GRB100507 (Ref. 95), GRB120323A (Ref. 96), GRB110920A (Ref. 97), and GRB101219B (Ref. 98).

Many of these fits used an "advanced" version of Ryde's original "hybrid" model, by modeling the nonthermal part of the spectra with a "Band" function. This implies that these models are semi-physical (the thermal part has a clear physical origin, while the origin of the "Band" function is unclear). A repeated result is that, using these fits, the thermal component often does not coincide with the peak energy, but is observed as a lower energy "wiggle" on top of the "Band" low energy spectral slope (see Fig. 5). The observed thermal flux is at the range of tens of % of the total flux. This result, though may be attributed to a selection bias: if the fraction of thermal photons was lower than that, they could not have been detected. Recently, it was shown that the "Band" function in these fits can be associated with (slow cooled) synchrotron emission, at least in a few bursts.[99,100]

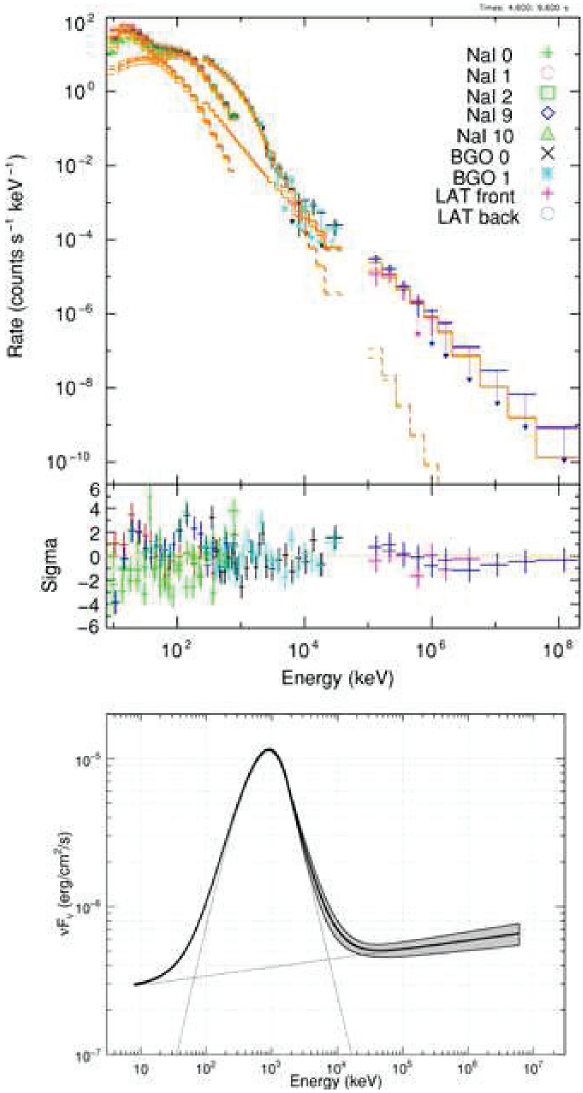


Fig. 4. Spectrum of GRB090902B at 4.6–9.6 s after the trigger, adopted from Ref. 77 show clear thermal component.

There are therefore two key conclusions from these works.

(1) The main conclusion is that a thermal component is most likely ubiquitous. A main reason why it is not observed in many bursts is simply that many fits are done using templates that do not enable its discovery. A secondary reason is that (by definition) most bursts will be seen with very low photon statistics, that will not enable its detection.
(2) In most cases in which a thermal component was detected, it was

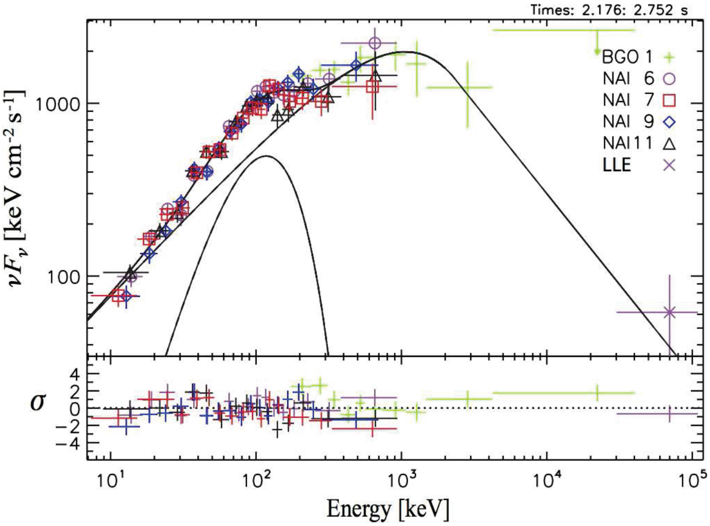


Fig. 5. The spectra of GRB110721A is best fit with a "Band" model (peaking at $E_{\rm peak} \sim 1$ MeV), and a blackbody component (having temperature $T \sim 100$ keV). The advantage over using just a "Band" function is evident when looking at the residuals. (Taken from Ref. 93.)

accompanied by a nonthermal part, which typically was seen to be with higher flux. Furthermore, for most bursts in which a thermal component is observed, the peak of the thermal component does not coincide with the spectral peak. In several cases, the observed peak of the "Band" spectrum is too energetic to be explained by a thermal component.[101]

3.2. *Thermal emission observed at late-times*

Several authors reported a thermal component that was detected not in the γ-rays, but rather in the X-ray band. In these bursts, the typical temperature of the thermal component is at the $\sim$ keV range, as opposed to ~ 100 keV observed in the bursts discussed above. Furthermore, in these bursts the thermal component was observed to last hundreds of seconds, extending well into the afterglow phase. In this category, there are both low luminosity GRBs such as GRB060218 (Refs. 102 and 103) or GRB100316D (Ref. 104) but also many GRBs with typical luminosities, as reported, e.g. by Refs. 105–111.

Common to all GRBs in this category are (1) the fact that the thermal component is observed well into the afterglow phase; and (2) the inferred values of the Lorentz factors are at least an order of magnitude lower than that of "standard" GRBs: $\Gamma \lesssim$ few tens, and in some cases much lower, $\Gamma \gtrsim 1$. These results indicate that the physical origin of the thermal component in these bursts may be different than those bursts in which a thermal component is seen at higher energies. Leading models are supernovae shock breakout and emission from the emerging cocoon (which we will briefly discuss below). Overall, these detections imply that there is more than a single way of producing a thermal component in GRBs.

3.3. *Indirect evidence*

As explained above, direct detection of a thermal emission (observation of a "Planck" function) is still relatively rare. A major part of this is attributed to the use of the "Band" fitting function. A second reason is the lack of sufficient photon statistics; and a third possible reason (which will be described below) is possible various physical mechanisms that act to smear the pure "Planck" function. In fact, such mechanisms, if indeed operate, will make it very difficult to claim any detection of the thermal component.

Nonetheless, there are ample of indirect evidence for the existence of a thermal emission component in the vast majority of bursts. These evidence are based on the fact that the "Band" fit, by itself, does not provide any physical meaning. Thus, it needs to be interpreted in the framework of one (or more) known radiative mechanisms. Clearly, there is more than one way of interpreting the data. Nonetheless, some of the key observed properties cannot be explained in the framework of any of the alternative radiative mechanisms, or that they require "fine tuning" of the model parameters. These same properties can, in some cases, be much easier explained if one assumes that the observed spectrum is composed of a (modified) Planck component.

Among the key observed properties, one finds the following:

(1) *Steep low energy spectral slopes.* As discussed above, when fitting the prompt spectrum with a "Band" function, the average low energy spectral slope obtained is $\langle\alpha\rangle = -1$. The low energy spectral slope of about 85% of the GRBs fitted in this way are found to be steeper than -1.5, which is the upper limit allowed by synchrotron emission (in the "fast cooling" regime).[20,22,35–38,82,100,112] This result therefore implies that the (optically thin) synchrotron emission cannot be responsible to this emission, at least without significant modifications to its underlying assumptions.

(2) *Spectral width.* Recent works measured the spectral width of the prompt emission. The advantage of this method is that it is not sensitive to any assumptions about the initial particle distribution (power law or not) or to the question of fast versus slow cooling. The results of these works (Ref. 72 and 73) clearly indicate that synchrotron emission — even from a Maxwellian distribution of particles produces a much wider spectrum than is observed. We point out that a full assessment of these results require direct fits to the synchrotron model, in order to overcome the ambiguity caused by the forward-folding technique.

(3) *Observed correlations.* Several correlations have been reported between the peak energy and the total energy or luminosity of a GRB (e.g. Refs. 39, 40, 113 and 114). Within the framework of the "synchrotron" model, the peak energy has a strong dependence on the free model parameters, $E_{\rm peak} \propto \Gamma\theta_{\rm el}^2 B$, where Γ is the bulk Lorentz factor, B is the magnetic field and $\theta_{\rm el}$ is the characteristic electron's temperature. Thus, first, there is no *a priori* reason why the peak

energy in all GRBs should be roughly at the sub-MeV range; the values of all these three parameters can vary substantially between the bursts. Furthermore, there is no *a priori* simple explanation to the observed peaks, without adding further assumptions.[41,42]

Explaining the observed peak with a thermal emission also requires tuning of the parameters (e.g. Refs. 55, 58 and 115), though it seem to be less restrictive than in the synchrotron model. Similarly, while thermal emission by itself cannot explain any of the observed correlations, it can do so with a relatively minor modifications (e.g. Refs. 116 and 119).

4. Theory

4.1. *Existence of a thermal component*

As discussed in Sec. 2 above, a thermal emission component was expected from the very early days following the realization that GRBs are cosmological. The huge optical depth at the base of the flow ($\tau \sim 10^{15}$) implies that any existing radiation will thermalize before escaping. Thus, a thermal component is an inherent part of the cosmological "fireball" model that was expected very early on.[11–13] This conclusion is not changed if the acceleration is mediated not by photons but by reconnection of strong magnetic fields that may exist in the innermost regions of the outflow.[16,120–122] None of the early models though provided any robust predictions about the relative importance of the thermal versus the nonthermal part. The expected thermal to nonthermal flux ratio depends on several unknown factors such as the radius of the photosphere, the radii of the energy dissipation episodes that lead to the emission of the nonthermal radiation, and the efficiency in producing the nonthermal photons. As a result, a variety of models exist, in which the relative strength of the thermal component vary — from dominant (e.g. Refs. 54 and 56) to sub-dominant (Refs. 55, 57 and 58).

Lacking any clear theoretical prediction, the values of the unknown models parameters were deduced from observations. The lack of a clear thermal signal in the observed data therefore led many people to consider a parameter space region in which a thermal component is sub-dominant. This can easily be obtained if the photospheric radius, $r_{\rm ph}$ is large enough, so that the thermal photons suffer substantial adiabatic losses prior to their escape. In such a scenario, it was concluded by many authors that the origin of the observed peak energy at the sub-MeV range is most likely due to synchrotron emission (for a very partial list, see Refs. 15, 23, 25, 26, 123–129). This line of reasoning was forced to be reconsidered once evidence began to accumulate for the inconsistency of the observed spectra with the theoretical predictions of the synchrotron model, in the early 2000's.

Even in those versions of the GRB "fireball" model in which only a small number of thermal photons is initially assumed, the theory allows the creation of a large number of thermal photons at a later stage. These photons can be created by friction between the jet components, or the jet component and the surrounding material. For example, free neutrons are expected to decouple the protons at small radii, below the photosphere, due to the lower cross-section for proton–neutron collision relative to Thomson cross-section. The friction between the neutrons and protons can result in energy dissipation, that eventually heats the jet and is capable of producing a large number of thermal photons (provided, of course that this energy dissipation occurs sufficiently below the photosphere).[130,131] It was further proposed that these photons may be associated with the peak energy.[132]

The association of long GRBs with core-collapse supernovae of type Ib/c (Refs. 102, 104, 133–137) led to the conclusion that at least long GRBs are associated with the death of massive star. In this so-called "collapsar" model (Refs. 138–144), the GRB jet drills its way through the collapsing material.[145,146] Interaction between the jet and the stellar envelope will lead to the formation of shock waves which will heat the plasma. These shock waves could potentially occur below the photosphere, thereby providing another channel for producing thermal photons.[147,148] A prediction of this model is the association of the thermal (and nonthermal) emission time with the time it takes the stellar material to collapse, which is of the order of ~ 10 s.[145,149–151] Once the jet completes its crossing through the stellar envelope, the external pressure rapidly drops, and the radii of these recollimation shocks would gradually increase until they would eventually disappear and the flow becomes free. However, this stage typically lasts a duration of a few sound crossing times, $\simeq 10$ s.[149,150,152] During this epoch, these shocks are roughly at their initial location, thereby are capable of producing a thermal emission component.

On its way out of the collapsing star, the jet heats and pushes the collapsing stellar material, forming a hot "cocoon", that expands outside of the stellar envelope following the emergence of the jet. This hot cocoon, which is much slower than the jet itself (estimates based on numerical models reveal $\Gamma_c \sim 10$) is optically thick, with optical depth that can reach few hundreds.[153] It may therefore be responsible for the late-time thermal emission observed.[154] Finally, additional source of thermal emission may be the interaction of the relativistic GRB jet with the supernova shell.[155]

Thus, to summarize this section, in fact there is a consensus that a thermal emission component should exist in cosmological GRBs; this is agreed by many different models that consider different dynamical scenarios. None of the currently existing models, though, give any robust prediction on the expected strength of the thermal component, and the models differ in the relative importance of this component. Lacking a clear theoretical prediction, in fact in nearly all models the role of a thermal component is left as a free parameter that is scaled by observations.

4.2. *Broadening of the thermal components*

The fact that thermal emission was predicted to exist (and in some models predicted to be dominant) in the GRB prompt spectra naturally raises the question of its lack or weakness in the observed spectra. One immediate answer for its lack is adiabatic energy losses below the photosphere. As discussed above, these are expected in parameter space region in which the photospheric radius is very large. In such a case, the thermal photons lose their energy below the photosphere at the expense of the plasma's bulk kinetic energy. As a result, when the thermal photons decouple the plasma at the photosphere, both their temperature and thermal flux are low — close to, or even below the detection limit. This view was the leading view up until the first half of the 2000's, and is still a leading view by several scientists.

In this scenario, the dominant emission processes responsible for the observed signal therefore take place way above the photosphere. As such, they must be nonthermal in nature: the leading mechanisms are synchrotron, inverse Compton or, alternatively, emission from energetic hadrons. These processes follow episode(s) of energy dissipation (either kinetic or magnetic), which accelerate particles that produce the nonthermal radiation. According to this picture, the thermal component plays a very small or negligible role in shaping the observed spectra.

As explained above, this view was challenged in the early 2000's by various observations that were found to be in contradiction to the optically thin emission model predictions. One branch of solutions was, and still is, to modify one or more of the underlying assumptions of the optically thin models (see discussion in Sec. 3 above). An alternative approach is to look at mechanisms that may modify the thermal component itself in such a way that the modified spectral shape will resemble the observed one. If this line of reasoning is correct, the thermal emission component in fact plays a very central role in determining the observed spectra. The observed GRB spectra deviates from a "Planck" function (and thus seem as being nonthermal) due to various physical processes and geometrical effects.

In this section, we discuss some possible mechanisms that can act to modify the Planck spectra and their implications. Of course, if this is the correct scenario, it is much more difficult to prove the existence of an initial thermal component from the observed signal.

4.2.1. *Physical broadening and connection with the nonthermal spectra*

The most natural way of modifying a "pure" thermal component is by assuming that some part of the available energy (kinetic or magnetic) is dissipated below, or close to the photosphere. In fact, this is a natural part of the classical "fireball" model, in which the jet's kinetic energy is dissipated by instabilities in the outflow that lead to internal shock waves.[156,157] As we pointed out above, the "fireball" model (in all its different versions) does not provide strong constraints on the radii of the internal collisions between the outflow components that dissipate its kinetic energy. Part of these collisions may very well occur below the photosphere. Similarly, in models in which the outflow is highly magnetized, it is often assumed that the magnetic energy is dissipated at a constant rate from the fast magnetosonic radius onward (Refs. 120–122, 158), implying that part of the energy is dissipated below (but close to) the photosphere.

This dissipated energy is used (at least in part) to heat and/or accelerate plasma particle (electrons and possibly protons). A leading mechanism by which this dissipation can occur is by sub-photospheric (radiation-mediated) shock waves. The microphysics of particle acceleration in shock waves is of yet an open question. It was recently argued that sub-photospheric shock waves lack the structure that enable the acceleration of particles to high energies.[159] This, however, is expected to have only little effect on the emerging spectra, with respect to a scenario in which the particles are thermally heated by the shock waves. The reason is as follows. Once the particles are heated or accelerated, they radiatively cool extremely rapidly by upscattering the thermal photons. Due to the fact that below the photosphere, the number of thermal photons in the plasma is much greater than the number of particles, any energetic particle undergoes very many scattering, and therefore its cooling time is many orders of magnitude shorter than the dynamical time.[160] This means that the energetic particles will form a (quasi-) steady state very rapidly, which could be characterized by a (quasi-) Maxwellian distribution. Their temperature is determined by balance between the heating (whose details depend on the unknown details of the dissipation mechanism) on the one hand, and radiative cooling on the other hand. As long as the external heating is active, the particle's temperature will inevitably be higher than the temperature of the thermal photons in the plasma, that are not directly affected by the heating process. The result is the formation of a "two-temperature" plasma, containing a population of thermal photons with (comoving) temperature T'_γ, and a population of hotter electrons, characterized by a higher temperature, $T'_{\rm el} > T'_\gamma$.

As was discussed in Ref. 160, the particle's temperature is highly regulated, and depends very weakly on the model's parameters. It depends on only two parameters: (i) the ratio between heating rate and cooling rate (or, alternatively the energy density in the particles and the thermal photons), and (ii) the optical depth in which the dissipation takes place, which is governed by the radius of energy dissipation. The optical depth determines the number of scattering. For optical depth at the range $1 \lesssim \tau \lesssim 100$, the electron's steady state (comoving) normalized temperature is $kT'_{\rm el}/m_e c^2 \sim 0.1 - 1$.

The electron's distribution settle to the quasi steady state on a time scale much shorter than the dynamical time. Thus, during most of the dynamical time, the hotter electrons up-scatter the thermal photons, forming a secondary distribution at energies above T'_γ.[161–166] This is demonstrated in Fig. 6, taken from Ref. 161.

The resulting spectral shape depends on the optical depth in which the dissipation takes place. This is most easily understood when looking at the two extremes. If the radius at which the dissipation occurs is much greater than the photosphere ($\tau \ll 1$), then the thermal photons will have very few interactions with the energetic particles, and will be observed as an independent spectral component. Some thermal photons would serve as seed photons for Compton scattering by the energetic particles; the relative strength in the observed spectra would depend on the Compton Y parameter. In such a scenario, the energetic particles (that may be energized already below the photosphere, see Ref. 167) will radiate nonthermal emission. Two additional peaks may therefore be seen — due to synchrotron emission at lower energies, and synchrotron self Compton (SSC) peak at higher energies.

At the other extreme, in which the dissipation occurs in a very small radius ($\tau \gg 1$), the up-scattered photons will have ample of time to re-distribute their energy, and a new thermal distribution would emerge; simply, the energy given to the particles by the dissipation mechanism would be distributed among the particles and photons. The resulting spectrum will be thermal. Interestingly, in order for this to happen, it is enough that the dissipation takes place in region in which the optical depth is greater than few hundreds (see Fig. 6).

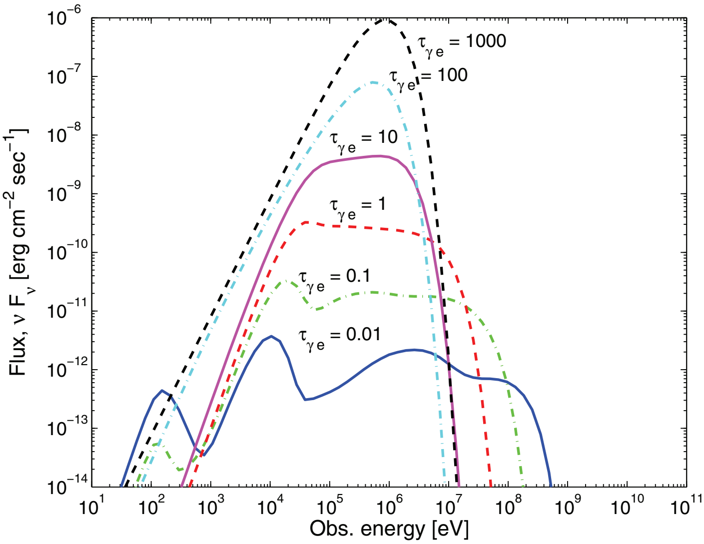


Fig. 6. (Color online) Time averaged broad band spectra expected following kinetic energy dissipation at various optical depths. For low optical depth, the two low-energy bumps are due to synchrotron emission and the original thermal component, and the high energy bumps are due to inverse Compton phenomenon. At high optical depth, $\tau \geq 100$, a Wien peak is formed at $\sim 10\,\text{keV}$, and is blue-shifted to the MeV range by the bulk Lorentz factor $\simeq 100$ expected in GRBs. In the intermediate regime, $0.1 < \tau < 100$, a flat energy spectrum above the thermal peak is obtained by multiple Compton scattering. Figure taken from Ref. 161.

The most interesting signal is observed if the dissipation occurs at intermediate values of the optical depth, $\tau \sim$ few–few tens. The addition of hot particles below the photosphere implies that some of the thermal photons will be up-scattered; but since by assumption τ is not very high, full rethermalization could not be achieved. As explained above, since the number of photons is much greater than the number of particles, each particle will undergo very many scattering, and so the particle's distribution will be quasi Maxwellian, as opposed to the photon distribution.

The initial thermal component is expected to somewhat weaken, as thermal photons are up-scattered; though the thermal component will maintain its original temperature. The main radiative process above the thermal peak will be inverse-Compton scattering, by the quasi thermal electrons. It is not hard to show that at the range $T_\gamma < E < T_{\rm el}$, the emerging spectra is a power law in energy. For a relatively large parameter space region, the resulting spectra will be flat.[161,168,169] Additional radiative mechanisms, such as synchrotron emission, may contribute to the lower energy part of the spectrum (below the thermal peak). Thus, in this case, one does not expect a continuation of the power law from above the thermal peak to below it. This is consistent with the negative results found when a search for a single power law extending both above and below the thermal peak were conducted.[170,171]

The results presented in Fig. 6 are calculated for a single dissipation episode. In explaining the complex GRB lightcurve, multiple such episodes (e.g. internal collisions) are expected. Thus, in reality, a variety of observed spectra, which are superposition of the different spectra that are obtained by dissipation at different optical depths are expected.[172]

The key results of this model do not change if one considers highly magnetized plasma.[164,168,169,173,174] A main difference between the highly magnetized models and the radiative dominated ones is the assumption that the source of energy that is used in heating the plasma is reconnection of magnetic field lines. As opposed to internal shock waves which are discrete in nature, the magnetic energy dissipation is expected to occur in a more gradual way along the flow. Thus, in this model, gradual heating of the plasma particles is expected from below the photosphere to above it. The resulting spectra is surprisingly similar to the one obtained in the discrete dissipation case; see Fig. 7, taken from Ref. 169.

The model of sub-photospheric energy dissipation thus has four very important advantages. First, it enables to explain some of the key properties of the observed spectra that cannot be explained in the framework of the optically thin, nonthermal emission models.[175,176] Equally important is the fact that the predicted spectra of this model are only weakly sensitive to many of the uncertainties, such as the unknown outflow magnetization, etc. This was investigated numerically by several authors for different dynamical models (Refs. 118, 177–179), as well as magnetization parameter (Ref. 180). Third, by slight modification of a single parameter — the optical depth in which the dissipation (or most of it) takes place, the emerging spectra can have very different shapes (see Figs. 8 and 9, taken

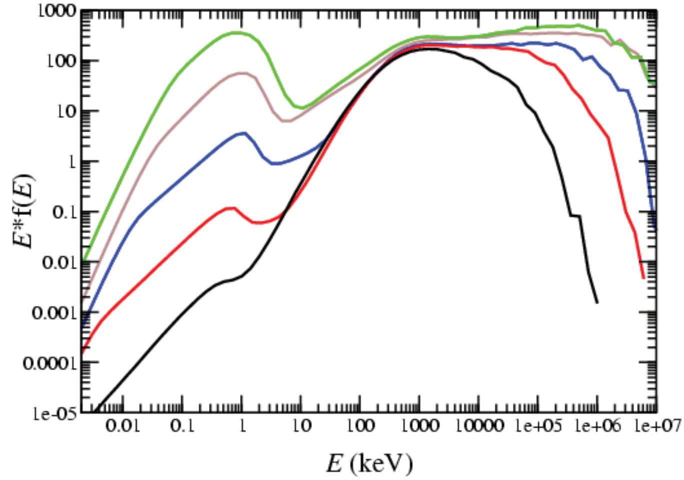
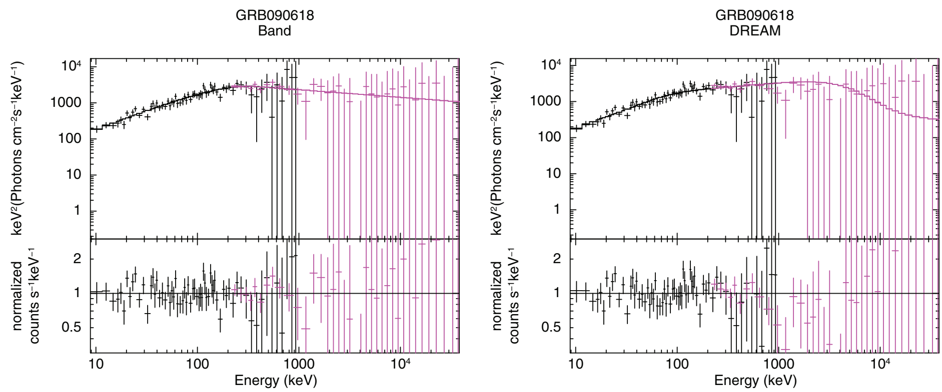


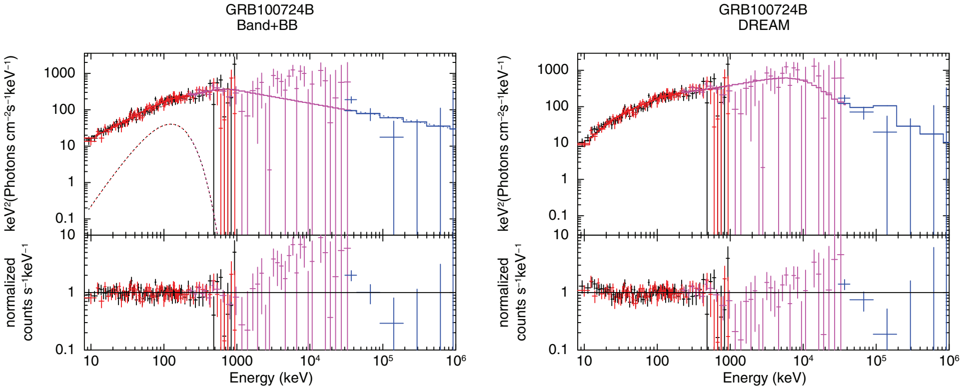
Fig. 7. Resulting spectra for dissipation occurring in highly magnetized models, as a function of the baryon load (or the magnetization). From bottom to top, the curves correspond to magnetization $\sigma_0 = 40, 50, 60, 70, 100$ (or corresponding baryon loading $\eta \simeq 250, 350, 460, 590, 1000$), respectively. The high σ_0 flows are characterized broader spectra. The model predicts that bright prompt optical and UV emission is accompanied by powerful ∼GeV emission. For bright optical emission, the optical spectrum is expected to be hard. Figure taken from Ref. 169.



(a) (b)

Fig. 8. Fits to GRB090618 at time bins 65.3–65.7 s. Left: Fit with traditionally "Band" function. Right: Fit to the same data with Dissipation with Radiative Emission as a table Model (DREAM) table model. These fits are based on tabulating the results of sub-photospheric energy dissipation code (Ref. 190), and using them as input in XSPEC. See Ref. 181 for details.

from Ref. 181). The sub-photospheric dissipation model therefore unifies different spectra that seem to be qualitatively different when fitted with a "Band" model into one framework. It can further be tested by comparing high energies spectral cutoffs.[182] Finally, as the origin of most of the photons is thermal, the efficiency problem in kinetic or magnetic energy conversion discussed above is much less se-



(a) (b)

Fig. 9. Fits to GRB100724B at time bins 25.8–33.5 s. Left: Fit with "Band" function plus black body. Right: Fit to the same data with DREAM model. See Ref. 181 for details. When fitting with a "Band" function, an addition of thermal component is required. However, fitting with sub-photospheric dissipation (DREAM) unifies this bursts' spectra with those of GRB090618 presented above, with the main difference being the optical depth in which the energy dissipation takes place.

vere. Most of the radiated energy is already in the form of thermal photons, and the dissipated energy acts to re-distribute them. Due to these advantages, this idea of sub-photospheric dissipation attracted a lot of attention in recent years (e.g. Refs. 116, 118, 130, 132, 147, 159, 162, 163, 165, 167, 175, 183–189). This is despite (but possibly, also due to) the fact that some of its key ingredients, such as the optical depth in which the dissipation takes place, are not understood from basic principles.

4.2.2. *Geometrical broadening*

Even if sub-photospheric dissipation does not exist in GRB jets, still the observed spectrum emerging from the photosphere is expected to somewhat deviate from a pure "Planck" shape. The reason is the "limb darkening" effect: The optical path of photons emerging from off the line of sight is larger than the optical path of photons emerging on-axis. As a result of that, photons that originate off-axis will be cooler than photons originating on-axis. As an observer cannot discriminate between the two photons, the integrated spectral shape will be a distorted "Planck" spectrum.

The limb darkening effect is well known in astronomy. Furthermore, the understanding that it will play some role in shaping the observed GRB spectra is also not new.[11,191,192] However, full treatment of this effect for relativistic outflows, as occur in GRB, was carried out only recently.[5,187,193–197] Comptonization of nonisotropic distributed photons near the photosphere leads to substantial deviation from the "Planck" spectrum.[198,199]

When considering spherical, relativistic explosion characterized by $\Gamma \gg 1$, one can show that the photospheric radius is a strong function of the angle to the line of sight:

$$r_{\rm ph}(\theta) \propto \left(\frac{1}{\Gamma^2} + \frac{\theta^2}{3}\right), \tag{1}$$

(see Ref. 193), where the proportionality constant is a function of the mass ejection rate.

This angular dependence implies that off-axis photons are observed at lower energies than on-axis photons, due to two effects. First, they suffer enhanced adiabatic losses as they travel longer path below the photosphere; and second, their Doppler boost is reduced relative to photons emitted on-axis. Combined together, these two effects lead to flattening of the Rayleigh–Jeans (low energy) part of the thermal spectrum.

An in-depth calculation of the expected spectra reveals the fact that the "photospheric radius", defined as the surface of last scattering is in fact ill-defined. A photospheric radius gives only a very crude approximation to the probability of photons to escape the plasma (which is equal to e^{-1} at $r_{\rm ph}$). In reality, photons have finite probability of being scattered at every location in space where particles exist. This realization led to the concept of a "vague photosphere" (See Fig. 10).[5,130,193,196,198–200] In a spherical explosion scenario, the effect of the vague photosphere on the observed spectral shape is not large; it somewhat modifies the

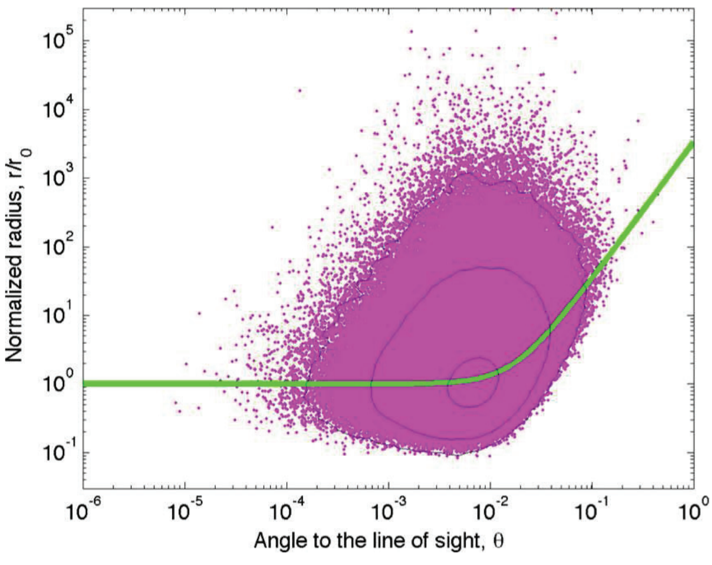
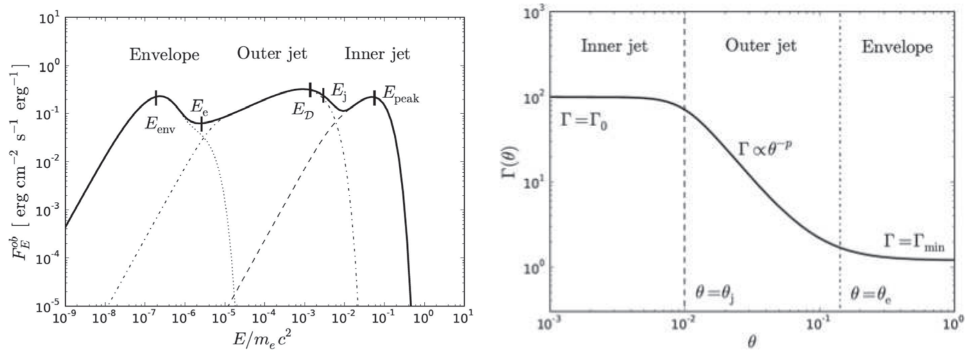


Fig. 10. (Color online) The green line represent the (normalized) photospheric radius $r_{\rm ph}$ as a function of the angle to the line of sight, θ, for spherical explosion (see Eq. (1)). The red dots represent the last scattering locations of photons ejected in the center of relativistic expanding "fireball" (using a Monte-Carlo simulation). The black lines show contours. Clearly, photons can undergo their last scattering at a range of radii and angles, leading to the concept of "vague photosphere". The observed photospheric signal is therefore smeared both in time and energy. Figure taken from Ref. 193.



(a) (b)

Fig. 11. Left. The expected (observed) spectrum from a relativistic, optically thick outflow. The resulting spectra does not resemble the naively expected "Planck" spectrum. Separate integration of the contributions from the inner jet (where $\Gamma \approx \Gamma_0$), outer jet (where Γ drops with angle) and envelope is shown with dashed, dotdashed and dotted lines, respectively. Right. The assumed jet profile. Figure taken from Ref. 200.

Rayleigh-Jeans part of the spectrum, that reads $F_\nu \propto \nu^{3/2}$ (Refs. 198 and 187). However, this assumes an idealistic scenario of spherical explosion with a smooth velocity profile. More realistic numerical models that consider outflow instabilities due to the interaction of the jet with the stellar envelope reveal a much more pronounced effect.[201,202] Furthermore, as will be shortly discussed below, for non-spherical explosion, the effect of the "vague photosphere" on the observed spectrum becomes dramatic.

Even for a spherical case, emission from the "vague photosphere" implies that late-time photons are more likely to originate from off-axis angles. This provides a robust prediction for the late-time asymptotic decay law (assuming that the central engine is abruptly shut), of $F(t) \propto t^{-2}$ and $T(t) \propto t^{-2/3}$ (Refs. 187, 193 and 194). This limit is obtained for the "pure" spherical scenario.

While the exact geometry of GRB jets, namely $\Gamma(r, \theta, \phi)$ are unknown, numerical simulations of jets propagating through the stellar core (e.g. Ref. 203) suggest a jet profile of the form $\Gamma(\theta) \sim \Gamma_0/(1 + (\theta/\theta_j)^{2p})$, at least for nonmagnetized outflows. Such a jet profile thus assumes a constant Lorentz factor, $\Gamma \sim \Gamma_0$ for $\theta \lesssim \theta_j$ (the "jet core", or inner jet), and decaying Lorentz factor at larger angles, $\Gamma(\theta) \propto \theta^{-p}$ (outer jet, or jet sheath). As the Lorentz factor is $\Gamma \propto L/\dot{M}$, such a profile can result from excess of mass load close to the jet edge, by mass collected from the star ($\dot{M} = \dot{M}(\theta)$), or alternatively by angle dependent luminosity.

The effect of angle-dependence mass loading, $\dot{M} = \dot{M}(\theta)$ on the observed photospheric signal is dramatic. While emission from the inner parts of the jet result in mild modification to the black body spectrum, photons emitted from the outer jet's photosphere dominate the spectra at low energies (see Fig. 11, taken from Ref. 200). For narrow jets ($\theta_j \Gamma_0 \lesssim$ few), this leads to flat low energy spectra, $dN/dE \propto E^{-1}$, which is independent on the viewing angle, and very weakly dependent on the exact jet profile. This result thus raises the possibility that the low energy slopes are in fact part of the photospheric emission itself, even if the observed power law is substantially different than a Rayleigh–Jeans. Furthermore, it raises the possibility that study of the low energy slopes can be used to infer the jet geometry.

A second aspect of this scenario is that the photospheric emission can be observed to be highly polarized, with up to $\approx 40\%$ polarization.[204–206] While inverse-Compton (IC) scattering produces highly polarized light, in spherical models the polarization from different viewing angles cancels. However, this cancellation is incomplete in jet-like models observed off-axis. Clearly, for an off-axis observer, the observed flux will be reduced; nonetheless, for a large parameter space region it is still high enough to be detected, in which case it will be seen to be highly polarized.[204]

A nonspherical jet geometry has a third unique aspect, which is photon energy gain by Fermi-like process. Below the photosphere, photons are scattered back and forth between the jet core and the sheath. Due to the difference in velocity in between the different regions, on the average the photons gain energy. This leads to a high energy power law tail, extending above the thermal peak.[200,207] Similar to the low energy case, this effect may potentially be used as a new probe in studying the jet geometry [Lundman *et al.*, in prep.].

4.3. *Implications of observations of a thermal component*

A great advantage of the photospheric emission is its relative simplicity. By definition, the photosphere is the inner most region from which electromagnetic signal can reach the observer. Thus, the properties of the emission site are much more constrained, relative, e.g. to synchrotron emission (whose emission radius, magnetic field strength and particle distribution are not known).

This advantage enables the use of an observed thermal component as a probe to some key parts of the underlying GRB physics. The GRB environment is complicated, and characterized by several processes of energy transfer that are obscured. Gravitational energy is converted to kinetic energy (jet launching); kinetic and possibly magnetic energy are dissipated; particles are heated; and radiation is emitted. We can only probe the final outcome — the observed spectra and its temporal evolution, from which all the previous stages and their physical ingredients need to be deduced.

The relative simplicity of the thermal emission is therefore of a great advantage, as it enables us to deduce several properties of GRB physics that are very difficult to probe. There are four main properties that have been discussed so far in the literature. First, if thermal photons are indeed the seed photons for Compton scattering, then by comparing the thermal part to the nonthermal part of the spectrum, one can directly probe the temperature of the hot electrons, as well as the optical depth in which these electrons were introduced into the plasma (which is where the energy dissipation took place). Thus, by fitting the data, one can provide information about the properties of the energy dissipation process. This had been discussed in Sec. 4.2.1 (see Ref. 181).

Second, as discussed in Sec. 4.2.2, low and high energy spectral slopes as well as polarization measurements may be used to probe the geometry of GRB jets, and possibly even the viewing angle. Nonetheless, the ability to obtain similar spectral slopes by more than a single way implies that further theoretical work is needed before firm conclusions could be drawn. Third, the properties of the thermal emission could be used to infer the dynamics of the outflow; and fourth, it may even be used to constrain the outflow magnetization. Here, we discuss these last two probes. A word of caution: in order to perform these analyses, one has to be able to clearly identify the properties of the thermal component (temperature and flux). Thus, these analysis can only be performed if the thermal component is not strongly distorted by sub-photospheric dissipation or geometrical effects.

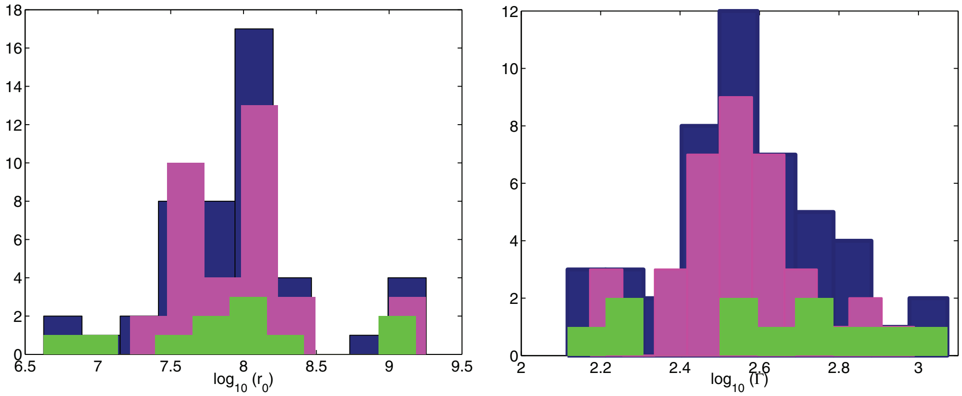
4.3.1. *Probing outflow dynamics*

In the framework of the "hot" fireball model in which the magnetic field is dynamically sub-dominant, the (1-d) photospheric radius is a function of only two parameters: the luminosity (which can be measured once the distance is known) and the Lorentz factor. The photospheric radius is related to the observed temperature and flux via $r_{\rm ph}/\Gamma \propto (F_{bb}^{ob}/\sigma T^{ob^4})^{1/4}$, where σ is Stefan's constant, and the extra factor of Γ^{-1} is due to light aberration. Since $r_{\rm ph} \propto L\Gamma^{-3}$, measurements of the temperature and flux for bursts with known redshift enable an independent measurement of the Lorentz factor at the photosphere, Γ, the photospheric radius, $r_{\rm ph}$, and the acceleration radius, r_0.[208] These, in turn, can be used to determine the full dynamical properties of the outflow.

A very interesting result is that by using this method, it is found that r_0, the size of the jet base ($\Gamma(r_0) = 1$), is $r_0 \gtrsim 10^8$ cm, nearly two orders of magnitude above the gravitational radius of 10 $M_\odot$ black hole (see Fig. 12).[88,208–210] While in many works it is assumed that r_0 is $\approx$ few gravitational radii, in fact, there is no evidence for that in the data; the shortest variability time scale observed in GRBs, $\delta t = r_0/c \gtrsim 10$ ms, with average value of ≈ 500 ms.[211] These results are therefore consistent with the results obtained by analyzing the thermal data.

The high value of r_0 may be interpreted as an indication for recollimation shocks that occur at this radius. These shocks originate from interactions between the outflow and the collapsing star, and are clearly seen in numerical simulations.[149,150,152,203,212,213] Thus, this result may serve as an indirect probe for the collapsar scenario.

Furthermore, the values of the Lorentz factor found using this method are at the range $10^2 \lesssim \Gamma \lesssim 10^3$. These values are similar to those inferred by other methods. The results obtained by analyzing the thermal component are aligned with recent constraints found by Ref. 185, that showed that the conditions for full thermalization takes place only if dissipation takes place at intermediate radii, $\sim 10^{10}$ cm, where



(a) (b)

Fig. 12. (Color online) Histograms of the mean values of $\log_{10}(r_0)$ (left) and $\log_{10}(\Gamma)$ (right) deduced from analyzed the properties of the thermal component in 47 GRBs. Blue are for the entire sample, while magenta are for 36 GRBs in category (III) sample only (which is a homogeneous sub-sample), and green are for 11 GRBs in categories (I) and (II). See Ref. 210 for details.

the outflow Lorentz factor is mild, $\Gamma \sim 10$. Interestingly, similar results albeit with somewhat lower values of the Lorentz factor, $\Gamma \sim 10^2$ were found when analyzing X-ray flares in a similar method.[214] Thus, overall, the results obtained point towards a new understanding of the early phases of jet dynamics.

4.3.2. *Probing outflow magnetization*

One of the key open questions in the study of GRBs is the role played by the magnetic fields. Within the framework of the original “fireball” model (Refs. 15 and 156), the flow accelerates to relativistic velocities by radiative pressure, and magnetic fields are dynamically unimportant. They do, though, play an important role in extracting the energy from the hot electrons that radiate via synchrotron mechanism.

In contrast to this picture, the leading mechanism for accelerating jets in active galactic nuclei (AGNs) is the Blandford–Znajek process (Ref. 215), which involves strong magnetic fields. It was therefore suggested that magnetic fields may be energetically dominated, hence play a central role in determining the dynamics of GRB as well.[120–122,158] This scenario could be valid if the progenitor of GRBs is rapidly spinning, strongly magnetized neutron star — the so called “magnetars”.[16,216–222] In this case, the main source of energy available for heating the particles is reconnection of the magnetic field lines (Refs. 16, 120 and 122), possibly enhanced by turbulentic outflows.[223]

There are several differences between magnetically dominated outflow and baryonic dominated outflows. One such difference is the location of the photospheric radius, which has a somewhat different dependence on the free model parameters.

A second difference is the fact that the strong magnetic fields serve as "energy reservoir", dissipating their energy gradually. This implies that the flux of the thermal photons is weaker in magnetized models in comparison with baryon-dominated ones. Based on this realization, it was argued that a weak or lack thereof of a thermal component could be attributed to a strong outflow magnetization.[41,56,224] This argument was used by Ref. 224 to claim that the outflow in GRB080916, which did not show any clear evidence for the existence of a thermal component, could be highly magnetized, with $\sigma \geq 20$ (see Fig. 13). This model further predicts high polarization (Ref. 225).

Furthermore, strong magnetic field would lead to rapid radiative cooling of the energetic particles. This puts strong constraints on the properties of the particle acceleration mechanism that could reproduce the observed signal.[174] In a recent work (Ref. 226), it was shown that in the framework of continuous magnetic reconnection model, conditions for full thermalization do not exist in the entire region below the photosphere. As a result, the produced photons are up-scattered, and the resulting peak of the Wien distribution formed is at $\gtrsim 10$ MeV. This again leads to the same conclusion as drawn above, namely that identification of thermal component at energies of $\lesssim 100\,\mathrm{keV}$ must imply that the outflow cannot be highly magnetized.

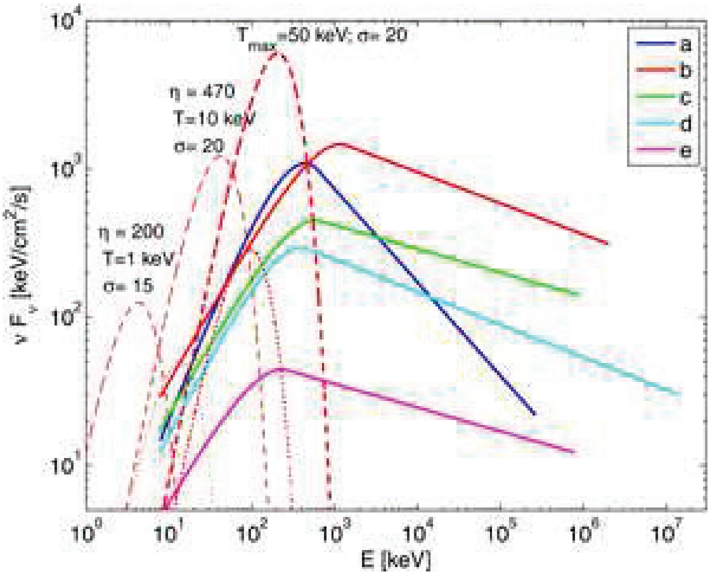


Fig. 13. (Color online) Observed Band-function spectra for the five epochs of GRB080916C, taken from Ref. 227 (color solid) and the predicted lower limits of the photosphere spectra (red dashed) for different parameters for the epoch (b) within the framework of the baryonic fireball models. Red, thick-dashed curve: the internal shock model with $\delta t^{\mathrm{ob}} = 0.5$ s, corresponding to $T^{\mathrm{ob}}_{\mathrm{ph}} = 50$ keV; red, thin-dashed curves: for $T^{\mathrm{ob}}_{\mathrm{ph}} = 10, 1\,\mathrm{keV}$. The suppressed photosphere spectra are plotted by red, dotted curves, with the required values marked. Figure taken from Ref. 224.

5. Summary

A major breakthrough in our understanding of GRB prompt emission occurred in recent years with the realization that a thermal emission component exists on top of the over all nonthermal spectra. This realization opens up a completely new window into studying the physics of GRBs. In this short review, we highlighted some of the major aspects of this realization.

In Sec. 2, we pointed out to the fact that thermal emission was predicted already by the very early models of cosmological GRBs. It was later abandoned, as the observed spectra did not reveal a clear evidence of a "Planck" spectrum. However, it was re-considered in the early 2000's, following the realization that known nonthermal models suffer difficulties in fitting the observed data.

In Sec. 3, we described the observational status. There are several key results that need to be emphasized.

(1) The "Band" function provides good fits to most of GRB data, with only a relatively small fraction of GRBs that are of an exception. Nonetheless, the use of "Band" fits is highly misleading, as the "Band" model, from its very nature, is not capable of capturing any "wiggles" that may indicate the existence of a thermal emission. Furthermore, by definition, most bursts are detected close to the detection limit, in which case a weak thermal signal could not be observed.
(2) The fraction of GRBs in which a thermal component is detected increases with their observed luminosity. In most cases, in which a thermal component was detected, it was accompanied by a nonthermal emission. Furthermore, attempts to associate a sole nonthermal radiative mechanism to the observed spectra show inconsistency. These facts suggest that a thermal component is in fact very ubiquitous among GRBs.
(3) In all cases in which a thermal component was detected, both the temperature and thermal flux show well defined, repetitive temporal behavior, which is distinct from the nonthermal behavior. Although a theory that can explain this behavior is of yet incomplete, the repetitive behavior strengthen the interpretation of this component to be distinct.
(4) As a consequence, in order to make further progress, the logical step is to abandon the "Band" fits, and fit the data with physically-motivated models, that would include a thermal component, in addition to nonthermal emission processes. Several such models already exist, though they are still not in wide use. We can anticipate that with a more wider use, the existence of a thermal emission would become more and more clear.

Section 4 was devoted to an overview of the theoretical status. We pointed out that all leading theoretical models predict the existence of a thermal component, though no existing theory provides robust predictions about its strength. We then discussed various mechanisms that act to broaden the naively expected "Planck" function. As we showed, the "Planck" function may be so heavily distorted, that the resulting spectra would resemble the observed one. If this is indeed the case, then the thermal component plays a very central role in the entire observed prompt emission. In particular, we discussed the following points:

(1) Sub-photospheric energy dissipation is expected by many theoretical models. If the dissipation occurs not too-far below the photosphere, a "two-temperature" plasma emerges. In this case, there is a complicated connection between the thermal and nonthermal parts of the spectrum, as the thermal photons serve as seed photons for scattering by the hotter electrons. In this scenario, the leading radiative process above the thermal peak is IC scattering, rather than synchrotron.
(2) Relativistic "limb darkening" effect will further broaden the "Planck" spectra, irrespective of any energy dissipation that may or may not exist. Study of this effect led to the realization that the photosphere is, in fact "vague". While this results in only a minor modification to the "Planck" function in the spherical explosion case, it has a dramatic effect on the observed spectra if the outflow is not spherical. In this later case, photons can be accelerated by Fermi-like process below the photosphere.
(3) If the thermal emission is not strongly distorted, its properties can be used as a direct probe of the dynamics of the outflow. In particular, it can provide an indirect evidence for the "collapsar" model. If the outflow is highly magnetized, the thermal component is expected to weaken. Therefore, weak, or lack of thermal component can be used to constrain the outflow magnetization.

Nearly all of the realizations described here — both observational and theoretical — occurred only in the last decade or so. Thus, while a major progress had been made in recent years, clearly there are still several very important open questions in the study of GRBs. These include, e.g. the questions of progenitor, magnetization and energy dissipation.

It is difficult to state at this point the role that thermal emission will play in the future in resolving these issues. A main concern is the fact that the observed signal is often degenerated, namely it can be explained by more than one model. A good example is the fact that a weak "Planck" component can result from either (1) adiabatic losses; (2) strong distortion due to sub-photospheric dissipation; or (3) strong magnetization. Each of these models is very different in nature than the other ones. Thus, one needs to combine the thermal signal with additional clues — both observational (broad-band nonthermal signal, temporal evolution) as well as theoretical models, in order to achieve a comprehensive understanding of GRB physics. Nonetheless, we believe that it is clear that the study of a thermal component will continue to provide new probes that will eventually lead to answering the open questions.

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