A thermal radiative component is likely to accompany the first stages of the prompt emission of gamma-ray bursts (GRBs) and X-ray flashes. We analyse the effect of such a component on the observable spectrum, assuming that the observable effects are due to a dissipation process occurring below or near the thermal photosphere. For comparable energy densities in the thermal and leptonic components, the dominant emission mechanism is Compton scattering. This leads to a nearly flat energy spectrum \( nF_n \approx \nu^0 \) above the thermal peak at approximately 10–100 keV and below 10–100 MeV, for a wide range of optical depths \( 0.03 \lesssim \tau \lesssim 100 \), regardless of the details of the dissipation mechanism or the strength of the magnetic field. For higher values of the optical depth, a Wien peak is formed at 100 keV to 1 MeV. In particular, these results are applicable to the internal shock model of GRBs, as well as to slow dissipation models, e.g. as might be expected from reconnection, if the dissipation occurs at a sub-photospheric radii. We conclude that dissipation near the thermal photosphere can naturally explain (i) clustering of the peak energy at sub-MeV energies at early times, (ii) steep slopes observed at low energies, and (iii) a flat spectrum above 10 keV at late times. Our model thus provides an alternative scenario to the optically thin synchrotron–synchrotron self-Compton model.

1. Introduction

The widely accepted interpretation of gamma-ray burst (GRB) phenomenology is that the observable radiation is due to the dissipation of the kinetic energy of a relativistic outflow, powered by a central compact object. The dissipated energy is converted to energetic electrons, which produce high-energy photons by synchrotron radiation and inverse Compton (IC) scattering. While being consistent with a large number of GRB observations (Band et al. 1993; Tavani 1996; Preece et al. 1998), two concerns are often raised: the gamma-ray break

* Author for correspondence (apeer@science.uva.nl).

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energy of most GRBs observed by BATSE is in the range of 100–300 keV (Preece et al. 2000; Kaneko et al. 2006). It is thought that clustering of the peak emission in this narrow energy range requires fine tuning of the fireball model parameters. In addition, there is increasing evidence for low-energy spectral slopes steeper than the optically thin synchrotron or synchrotron self-Compton (SSC) model predictions (Crider et al. 1997; Preece et al. 1998; Frontera et al. 2000; Ghirlanda et al. 2003; Ryde 2005).

Motivated by this evidence, an additional thermal component was suggested which may contribute to the observed spectrum (Mészáros & Rees 2000; Mészáros et al. 2002; Rees & Mészáros 2005). This radiation originates from the base of the relativistic flow and is advected outward as long as the flow material remains opaque. As shown by Rees & Mészáros (2005), dissipation processes can occur at small enough radii, where the optical depth is high. As a result, the created spectrum is significantly different from the optically thin synchrotron–SSC model predictions. A detailed analysis of the resulting spectrum under these conditions was carried out by Pe’er et al. (2005, 2006). Here, we give a short summary of the main calculations and results of these works.

2. Energy dissipation and thermal component

We assume that the dissipation process producing the GRB prompt emission occurs at radius \( r_d \) which is comparable to the photospheric radius \( r_{ph} \), below which the optical depth to scattering \( \tau_{\gamma e} (r) \) is larger than unity. At \( r_d \), the plasma contains a thermal component of low-energy photons at a normalized comoving temperature \( \theta = kT / m_e c^2 \). The value of \( \theta \) depends on the dissipation radius, and characteristic values are in the range of \( 10^{-5} \)–\( 10^{-2} \). We parametrize the energy density in the thermal component as a fraction \( A \) of the dissipated energy density given to the accelerated electrons, \( A \equiv u_{ph} / u_{el} \sim 1 \) (Pe’er et al. 2005). The (unspecified) dissipation mechanism accelerates electrons to characteristic Lorentz factor \( \gamma_m \) during the comoving dynamical time, \( t_{dyn} \). The electrons lose their energy by IC scattering the thermal photons in the Thompson regime and by synchrotron emission, and cool down to \( \gamma_f \sim 1 \) on a loss time

\[
\frac{t_{loss}}{t_{dyn}} = \frac{3}{4A(1 + S)\gamma_m \tau_{\gamma e}},\tag{2.1}
\]

where \( S \equiv P_{syn} / P_{IC} \) is the ratio of synchrotron to IC power and \( \tau_{\gamma e} \) is the electron scattering optical depth at \( r_d \). Thus, for \( \tau_{\gamma e} > 1 \), electrons accumulate at \( \gamma_f \approx 1 \) on a time shorter than the dynamical time.

As electrons cool down, they IC scatter the thermal photons to high energies. These photons eventually regulate the final electrons’ momentum \( \gamma_f \beta_f \), which at a steady state is obtained by equating the electrons’ energy loss rate and the energy gain rate. Assuming that the bulk of the photons undergo \( n_{sc} \) scattering, the steady-state electrons’ momentum is calculated using

\[
(\gamma_f \beta_f)^2 e^{A/3(\gamma_f \beta_f)^2 n_{sc}} = \frac{3}{4A(1 + S)\tau_{\gamma e}}.\tag{2.2}
\]
For optical depths not much larger than a few, the exponent on the left-hand side of equation (2.2) can be approximated as 1. In this approximation, the steady-state electron momentum is given by

$$g f b f (n_{sc} (10)^z \frac{3}{4} A(1 + S) \tau_{\gamma e})^{1/2} \approx 0.3 A_0^{-1/2} \tau_{\gamma e,1}^{-1/2},$$

where \( \tau_{\gamma e} = 10^4 \tau_{\gamma e,1} \) and \( A = 1 A_0 \) is assumed. For optical depths higher than approximately 100, photons are upscattered to high energies above the Thompson regime. In this case, the energy is spread among the electrons and the photons, and the electrons’ steady-state momentum is

$$g f b f 0.44 \text{ in all cases.}$$

The value of the optical depth \( \tau_{\gamma e} \) depends on the uncertain values of the free model parameters of the unspecified dissipation scenario, such as (in the internal shock model scenario) the isotropic equivalent luminosity \( L \) and the bulk Lorentz factor of the flow \( \Gamma \). Once the value of \( \tau_{\gamma e} \) is specified, the above analysis holds and the final electrons’ momentum is not directly dependent on the values of any additional free parameters.

We calculated numerically the photon and particle energy distribution using the detailed time-dependent numerical model described by Pe’er & Waxman (2004, 2005). The results are presented in figure 1, which demonstrates the accumulation of electrons at \( g f b f 0.1–0.3 \) for various values of the optical depth, \( \tau_{\gamma e} = 1–100 \).

3. Photons spectrum

The resulting spectrum above the thermal peak can be approximated in the following way. For \( g f b f 1(\tau_{\gamma e} \leq 1) \), the energy of a photon after \( n_{sc} \) scattering is

$$\epsilon_{n_{sc}} \approx \epsilon_0 (g f b f 2 n_{sc},$$

where \( \epsilon_0 \) is the initial photon’s energy. At the end of the dynamical

\[\text{(Pe'er & Waxman, 2004, 2005)}\]
time, the number density of photons that undergo $n_{sc}$ scattering is $n_{ph,sc} \approx n_{ph,0} \tau_{\gamma e}^{n_{sc}}$. For $A$ not much different from 1 and $S$ not much larger than 1, we use the relation $(\gamma_{\pi} \beta_{\pi})^2 \approx \tau_{\gamma e}^{-1}$ to find that $\log(n_{ph,n_{sc}}/n_{ph,0}) = (-1) \times \log(e_{n_{sc}}/e_0)$. Since $n_{ph,n_{sc}}$ is the number density of photons in the energy range $e_{n_{sc}} \ldots e_{n_{sc}} + de_{n_{sc}}$, we conclude that $\varepsilon d\varepsilon/d\varepsilon \propto \varepsilon^{-1}$ or $\nu F_{\nu} \propto \nu^{0}$ above the thermal peak and below $\varepsilon_{\text{max}} = \gamma_{\pi} m_e c^2$ (in the plasma frame).

For high values of optical depth, $\tau_{\gamma e} \gtrsim 100$, the photons receive nearly all of the electrons’ energy and a Wien peak is formed at the comoving energy,

$$\varepsilon_{WP} \approx 3\theta m_e c^2 \times (1 + A^{-1}) \approx 10 \text{ keV},$$

irrespective of the value of the optical depth. We show in figure 2 the results of a detailed numerical model that produces the spectrum for a wide range of values of the optical depth. The observed spectrum is blue shifted compared to the plasma-frame spectrum by the bulk Lorentz factor of the flow ($\Gamma = 100$ in the results presented in figure 2). Two additional effects that reduce the observed energy and are not considered in this figure are the cosmological redshift and an additional energy loss of the photons to the bulk motion of the plasma in the case of high optical depth. It was shown by Pe’er & Waxman (2004) that for $\tau_{\gamma e} \approx 10^2 \text{--} 10^3$, this effect reduces the observed photon energy by a factor of 2–3.

4. Summary

We have considered the effect of a photospheric component on the observed spectrum after kinetic energy dissipation that occurs below or near the thermal photosphere of the outflows in GRBs or X-ray flashes. For Thompson optical
depths $\tau_{\gamma e} \geq 1$, the electrons accumulate at $\gamma_t \beta_t \approx 0.1$–0.3, with only a weak dependence on the unknown parameter values. For $\tau_{\gamma e}$ smaller than a few tens, an approximately flat energy per decade spectrum is obtained above a break energy at few tens to hundreds of keV and up to sub-GeV, while steep slopes are obtained at lower energy. For $\tau_{\gamma e} \approx 100$, the balance between Compton and IC scattering by these electrons results in a spectral peak at approximately 1–10 keV in the plasma frame (sub-MeV in the observed frame). It was recently shown by Thompson et al. (submitted) that this result, combined with an additional constraint on the jet opening angle, can be used as a possible explanation to the $E_{\text{peak}} - E_{\text{iso}}$ relation (Amati et al. 2002).

Our theoretical and numerical results emphasize the important role of IC scattering in the formation of the spectra in scenarios involving a significant thermal component. As a result, the observed spectral slopes are significantly different from the synchrotron model prediction. The flat energy spectra obtained for intermediate values of the optical depth and the Wien peak obtained at high values are consistent with a large number of observations. Thus, our model provides an alternative scenario to the optically thin synchrotron–SSC model. Further details as well as discussions about synchrotron emission, the role played by pairs and comparison of the resulting spectra under different dissipation mechanism are found in Pe'er et al. (2005, 2006).

References


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