On diffusive photospheres in gamma-ray bursts

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Photospheric emission from relativistic outflows may originate in two different regimes: photon decoupling within the outflow or radiative diffusion. I will discuss observed thermal component in the early afterglows of gamma-ray bursts as emission from such diffusive photospheres. In addition, I will discuss implications of photon diffusion for dissipative models of GRBs.

Keywords: thermal radiation, gamma-ray bursts

1. Introduction

Gamma-ray bursts (GRBs) are strong and short flashes of hard radiation originating at cosmological distances. Since their discovery a number of dedicated space observatories and ground based telescopes are constantly monitoring the sky daily reporting new bursts and measuring distance to their host galaxies. GRBs come in two kinds: short and long, with their possible progenitors being binary neutron star mergers and collapsing massive stars reaching the endpoint of their evolution, respectively. Observed emission in GRBs is well separated in two distinct episodes: brief and highly irregular prompt phase with dominant hard X-ray and $\gamma-$ radiation, and smoothly decaying long lasting afterglow emission with broadband spectra, ranging from radio waves up to sub-TeV energies. Extremely large energies released in γ-rays ($\leq 10^{54}$ erg) as well as a short variability time (≤ 10 ms) point to ultrarelativistic outflows giving rise to the observed emission [1].

Prompt emission spectra are non-thermal, their origin is usually associated with the synchrotron mechanism in relativistic shock waves [2]. Photospheric models with possible dissipation of kinetic energy of the outflow are attractive alternative to the synchrotron models since observation of thermal radiation allows determination of basic hydrodynamic characteristics of the outflow from which these bursts originate [3,4]. The photons in these models are trapped and advected with the outflow until it becomes transparent. In many GRBs subdominant thermal component was detected during their prompt emission, while in several GRB 090902B observed spectrum is almost thermal [5,6].

Thermal components are also detected in time resolved spectra during the early afterglow in a number of GRBs [7–12]. So far several mechanisms to generate such emission are proposed. They include a shock breakout from a progenitor star or a stellar wind [13] and a hot cocoon formed when the relativistic jet emerges from the stellar surface[14,15]. Some authors argue that shock breakouts are not energetic enough and do not last long enough to explain observed thermal emission[11], leaving cocoons as a favourite model. In addition, there is an alternative proposal of a cloud or a clump with small mass, accelerated by the GRB outflow[16].

Most papers dealing with the photospheric emission, e.g.[17–23], for a review see[4], adopt the hydrodynamic model of a steady and infinite wind. However, finite duration of GRBs implies finite width of the wind. Winds of *finite duration* are classified as photon thin and photon thick[3,24,25]. Decoupling of photons from plasma in the latter case occurs simultaneously in the entire outflow, while in the former case photons are transported to the boundaries of the outflow by radiative diffusion, just like in nonrelativistic outflows, e.g. in supernova ejecta. Emission in this case originates not at the photospheric radius, but at smaller radii. The photon thick case, corresponding to the steady wind, appears to be justified for typical GRB parameters. Photon thin regime is not considered in the literature, as it is assumed that at large radii the outflow is spreading[26,27] due to strong velocity gradients initially present in the outflow, see e.g.[26,27]. Such spreading outflows indeed correspond to the photon thick case[28]. However, in absence of these gradients the outflow could be photon thin where decoupling of photons from expanding plasma occurs in the diffusive regime[25].

Radiative diffusion is known to be relevant for expanding ejecta in supernovae explosions[29], but was overlooked in the literature on GRBs. The purpose of the present work is to develop further the theory of photospheric emission[25], specifically focusing on the case when observed properties of such outflows are determined by the radiative diffusion of photons, and to confront it with the observational data.

The paper is organized as follows. The definition of the radius of photosphere is recalled in Section 2. Observational properties of diffusive photospheres are discussed in Section 3. The method allowing determination of initial radius and bulk Lorentz factor of the outflow is presented in Section 4. Observational properties of GRB cocoons are discussed in Section 5. Case studies of GRBs with thermal emission in the early afterglow is performed in Section 6. Discussion and conclusion follow. The paper is based on[30].

2. Relativistic photosphere

Consider a relativistic outflow launched at a radius R_0. The outflow is characterized by its activity time Δt, the luminosity L and mass injection rate $\dot{M}$. The associated thickness of the outflow is $l = c\Delta t$. The entropy in the region where the energy is released is parametrized by a dimensionless parameter $\eta = L/\dot{M}c^2$. Spherical symmetry is assumed, but generalization for anisotropic case with $\eta(\theta)$, where θ is the polar angle is straightforward. When $\eta \gg 1$ the bulk Lorentz factor changes with the radial distance as

$$\Gamma \simeq \begin{cases} \dfrac{r}{R_0}, & R_0 < r < \eta R_0, \\ \\ \eta \simeq \text{const}, & r > \eta R_0, \end{cases} \tag{1}$$

During both acceleration and coasting phases the continuity equation for the laboratory number density reduces to

$$n = \begin{cases} n_0 \left(\dfrac{R_0}{r}\right)^2, & R(t) < r < R(t) + l, \\ \\ 0, & \text{otherwise}, \end{cases} \tag{2}$$

where $R(t)$ is the radial position of the inner boundary of the outflow.

The optical depth for a spherically symmetric outflow is [25,31]

$$\tau = \int_R^{R+\Delta R} \sigma n \left(1 - \beta \cos\theta\right) \frac{dr}{\cos\theta}, \tag{3}$$

where $R + \Delta R$ is the radial coordinate at which the photon leaves the outflow, and θ is the angle between the velocity vector of the outflow and the direction of propagation of the photon, n is the laboratory number density of electrons and positrons, which may be present due to pair production. The dominant interaction of photons in our case is Compton scattering in the non-relativistic regime, so σ is the Thomson cross section.

Electron-positron-photon plasma with baryon loading reaches thermal equilibrium before its expansion starts [32,33]. With decreasing entropy η opacity due to electrons associated with baryons increases and eventually dominates over pair opacity. For the laboratory density profile (2) one has in the radial direction

$$\tau = \begin{cases} \dfrac{1}{6}\tau_0 \left(\dfrac{R_0}{R}\right)^3, & R_0 \ll R \ll \eta R_0, \\ \\ \dfrac{1}{2\eta^2}\tau_0 \left(\dfrac{R_0}{R}\right), & \eta R_0 \ll R \ll \eta^2 R_0, \\ \\ \tau_0 \left(\dfrac{R_0}{R}\right)^2, & R \gg \eta^2 R_0, \end{cases} \tag{4}$$

where

$$\tau_0 = \frac{\sigma L}{4\pi m_p c^3 R_0 \eta} = n_0 \sigma R_0. \tag{5}$$

The first two lines correspond to a *photon thick outflow* and the third line corresponds to a *photon thin outflow* [25].

The photospheric radius R_{ph} is defined by equating (4) to unity

$$R_{ph} = \begin{cases} R_0 \left(\frac{\tau_0}{6}\right)^{1/3}, & \tau_0 \ll \eta^3, \\ R_0 \frac{\tau_0}{2\eta^2}, & \eta^3 \ll \tau_0 \ll 4\eta^4 \frac{l}{R_0}, \\ (\tau_0 R_0 l)^{1/2}, & \tau_0 \gg 4\eta^4 \frac{l}{R_0}. \end{cases} \tag{6}$$

In eqs. (4) and (6) the regions of validity of different approximations are expressed either for radius or for parameters of the outflow. The crucial parameter which determines whether the outflow is photon thick or thin is the ratio

$$\chi = \frac{\tau_0}{4\eta^4}\frac{l}{R_0}. \tag{7}$$

The outflow is photon thin for $\chi \gg 1$ and it is photon thick otherwise.

3. Relativistic diffusive photosphere

The definition of the photosphere implies that at this position in space the outflow as a whole becomes transparent to radiation. However, emission emerges from the outflow when it is optically thick as well. Such emission is due to radiative diffusion, which transfers the energy from deeper parts of the outflow towards its surface. Naively one can think that such an effect is negligible in ultrarelativistic outflows. However, this is not the case[3]. Indeed, the comoving time, which photon takes to cross the outflow with comoving thickness $l_c = \Gamma l$ is $t_c = l_c^2/D_c$, where $D_c = c/3\sigma n_c$ is the diffusion coefficient, $n_c = n/\Gamma$ is the comoving density of the outflow. The radial coordinate of the outflow at this time is $R \simeq \Gamma c t_c$.

This diffusion radius is found in Ref.[25], and it is given by

$$R_D = \left(\tau_0 \eta^2 R_0 l^2\right)^{1/3}, \tag{8}$$

where eq. (5) has been used. It turns out to be always smaller than the photospheric radius of photon thin outflow, $R_D \ll R_{ph}$, so the radiation escapes such an outflow before it becomes transparent, just like in the supernova ejecta. In this sense the characteristic radius of the photospheric emission is not the photospheric radius found from (4), but the radius of diffusion (8). The probability distribution of last scattering of photons in diffusive photospheres is qualitatively different from the usual photospheric emission[24]. Besides, the comoving temperature of escaping radiation is different from the temperature at the photospheric radius. Applicability of the photon thin asymptotics, last line in eq. (6), can be written using eq. (8) as

$$l \ll \frac{R_D}{\sqrt{2}\eta^2}. \tag{9}$$

For larger thickness l photon thin asymptotics disappears, so in the limit $l \to \infty$ the stationary wind with photon thick asymptotics is recovered.

Adiabatic expansion implies[34] that the observed temperature of the outflow does not change while it is accelerating, and it decreases as $T_{obs} \propto R^{-2/3}$ at the coasting phase. Taking into account finite size of emitter and cosmological redshift one has[35]

$$T_{obs} = \frac{\xi}{1+z} T_0 \left(\frac{\eta R_0}{R_D} \right)^{2/3}, \tag{10}$$

where ξ is a numerical factor of order unity, z is cosmological redshift. In estimates below $\xi = 1.48$ is assumed following Ref.[35], which is found from the Monte Carlo simulations in the infinite wind approximation, though the value of ξ in the acceleration phase and in the photon thin case could be slightly different. The temperature at the base of the outflow is

$$T_0 \simeq \left(\frac{L}{4\pi c a R_0^2} \right)^{1/4}, \tag{11}$$

where $a = 4\sigma_{SB}/c$ is the radiation constant, σ_{SB} is the Stefan-Boltzmann constant. Finally, the duration of photospheric emission for a distant observer is

$$t_a^D = (1+z) \frac{R_D}{2\eta^2 c}. \tag{12}$$

In the photon thick case the duration of thermal emission is determined by the width of the outflow l, which is unconstrained. In the photon thin case this duration is given by eq. (12) and it is a function of the diffusion radius and the Lorentz factor.

The luminosity of photospheric component scales with radius as

$$L_{ph} = L_0 \left(\frac{\eta R_0}{R} \right)^{8/3}, \tag{13}$$

and the applicability condition of the photon thin case in eq. (6) and together with the definition of diffusion radius in eq. (8) imply for the luminosity of diffusive photosphere

$$L_{thin} < L_0 \left(\frac{R_0}{\eta l} \right)^{8/3} \ll L_0. \tag{14}$$

This means that thermal emission is much weaker than the emission of the prompt radiation, if γ-rays are produced with high efficiency there. For $l \sim R_0$ this condition strongly favours small values of η and, consequently, small Lorentz factors of the outflow.

4. Determination of initial radius and bulk Lorentz factor of the outflow

Assuming that the observed thermal component in early afterglows of some GRBs is of photospheric origin, one can estimate initial radius of the outflow directly from observations[35]. Indeed, in the ultrarelativistic regime one has

$$\mathcal{R} \equiv \left(\frac{F_{obs}^{BB}}{\sigma_{SB} T_{obs}^4}\right)^{1/2} = \zeta \frac{(1+z)^2}{d_L} \frac{R}{\Gamma}, \tag{15}$$

where R is the emission radius, d_L is the luminosity distance, ζ is a numerical factor of order unity. Following Ref.[35] $\zeta = 1.06$ is assumed for the estimates below. In Ref.[35] the emission radius R was associated with the photosphere of the *photon thick* outflows. However, this relation is valid for any ultrarelativistic emitter. Therefore, from eqs. (10), (15) and (11) the initial radius is

$$R_0 = \frac{4^{3/2} d_L}{\xi^6 \zeta^4 (1+z)^2} \mathcal{R} \left(\frac{F_{obs}^{BB}}{Y F_{obs}}\right)^{3/2}. \tag{16}$$

In the derivation of this results only two assumptions are made. First, the outflow should be coasting at ultrarelativistic speed, $\Gamma = \eta \gg 1$. Secondly, the relation $L = 4\pi d_L^2 Y F_{obs}$ is used, where Y is the fraction of the total luminosity L and the energy emitted in X and γ-rays *in the prompt phase*.

In addition to the initial radius R_0 an equation for the Lorentz factor can be obtained. Since the emitter radius for the *photon thin* outflows is the diffusion radius $R = R_D$, from eqs. (8) and (15) one obtains, see also Ref.[36]

$$\frac{\eta}{l} = \frac{\zeta^{3/2} (1+z)^3}{d_L^{1/2}} \left(\frac{\sigma Y F_{obs}}{m_p c^3 \mathcal{R}^3}\right)^{1/2}. \tag{17}$$

Therefore, the Lorentz factor can be determined if l is known. In particular case $l = R_0$ from (17) it follows the minimum Lorentz factor for which the photon thin case applies

$$\eta_{thin} = (1+z) \left(d_L \frac{Y F_{obs} \sigma}{m_p c^3 \mathcal{R}}\right)^{1/2} \frac{4^{3/2}}{\zeta^{5/2} \xi^6} \left(\frac{F_{obs}^{BB}}{Y F_{obs}}\right)^{3/2}. \tag{18}$$

The condition (9) determines the applicability limit of the photon thin case, so for $\sqrt{2}\eta^2 l = R_D$ the photon thick case is recovered[35]

$$\eta_{thick} = \left[\zeta (1+z)^2 d_L \frac{\sigma Y F_{obs}}{m_p c^3 \mathcal{R}}\right]^{1/4}. \tag{19}$$

Equations (17) and (18) allow the determination of the bulk Lorentz factor of the *photon thin* outflow, provided the measurement of the total flux F_{obs} and the parameter $\mathcal{R}$. Comparing eqs. (18) and (19) leads to the conclusion that the Lorentz factor inferred from the photon thin asymptotics is typically smaller than the one of the photon thick case; besides, it contains the inverse of the Y parameter, unlike a factor $Y^{1/4}$ in the latter case.

It is important to stress that from the theoretical point of view, given the total luminosity and the initial radius of the outflow one cannot distinguish between photon thick and photon thin cases as both sets of parameters are possible with different η and photospheric radius. These parameters are related by eq. (15), therefore independent observational information is required in order to differentiate between the two cases.

5. GRB cocoons

Consider typical parameters relevant for GRB jets which is penetrating the progenitor[15]. In what follows introduce the notation $A_x = A/10^x$, so the luminosity L_{52} stands for 10^{52} erg/s, which is the isotropic luminosity. While the entropy of the jet can take large values, the mixing between the progenitor and the jet lowers the entropy of the cocoon, so $\eta = 10$ is chosen, as a reference value. It is also likely that the entropy is a decreasing function of the angular distance from the jet. Assume that initial radius of the wind R_0 is given by the radius of the core of the progenitor WR star $R_0 \sim 10^9$ cm, and the thickness of the wind corresponds to the size of the WR star $l_{12} = 10^{12}$ cm[37]. The crucial parameter which determines whether the outflow is photon thick or thin is the ratio

$$\chi \simeq 29 L_{52} l_{12}^{-1} \eta_1^{-5}. \tag{20}$$

For $\chi \gg 1$ the outflow is photon thin, which is the case for our fiducial parameters. Considering the extreme dependence on η, for smaller η the condition is clearly satisfied. Hence the cocoon is in the photon thin regime and therefore the radiation from the cocoons is governed by radiative diffusion. The diffusion radius is

$$R_D \simeq 4.9 \times 10^{14} L_{52}^{1/3} \eta_1^{1/3} l_{12}^{2/3} \text{ cm}, \tag{21}$$

and the arrival time corresponding to this radius is

$$t_a^D = (1+z)\frac{R_D}{2\eta^2 c} \simeq 81.7(1+z) L_{52}^{1/3} \eta_1^{-5/3} l_{12}^{2/3} \text{ s}, \tag{22}$$

which is the typical duration of thermal emission observed in early afterglows of GRBs.

The observed temperature at the diffusion radius is

$$T_{obs} = 0.12 L_{52}^{1/36} R_9^{1/6} \eta_1^{4/9} l_{12}^{-4/9} \text{keV}, \tag{23}$$

which is also a typical temperature of thermal emission in early afterglows of GRBs[11].

Such inferred values of temperature and duration call for closer attention to the radiation properties of photon thin outflows.

6. Case studies

All GRBs reported in Ref.[11] with measured redshifts and thermal component detected in their early afterglows were considered, namely GRBs 060218, 090618, 101219B, 111123A, 111225A, 121211A, 131030A, 150727A, 151027A. Observed temperature, thermal flux and total flux were averaged for the entire duration of the thermal emission. The initial radius was found from eq. (16). Two values of the

Lorentz factor in photon thin, eq. (18), and photon thick, eq. (19), cases were determined. Then the minimum value of the Y parameter is found which allows the duration of the photospheric emission (12) to be not less than the observed duration of the thermal component. Only six cases allow both photon thick and photon thin interpretations for the photosphere; for other cases photon thin case does not apply because eq. (19) gives smaller Lorentz factor than eq. (18).

GRB 060218. This is a well studied nearby GRB [13] with record breaking duration of the thermal signal interpreted as the break out of a shock driven by a mildly relativistic shell into the dense wind surrounding the progenitor, see however Ref. [38,39]. The thermal emission in this burst with observed temperature $T_{BB} = 0.15$ keV may be also explained as a photosphere of a cocoon launched from initial radius 3.18×10^{11} cm with a mildly relativistic Lorentz factor $1.2Y^{-1} < \Gamma < 1.6Y^{1/4}$ emitting in the photon thin regime. This estimate of the Lorentz factor is in agreement with radio observation at 2 days, requiring $\Gamma \sim 2$ [40]. Given that the condition $\Gamma \gg 1$ is not satisfied, results of the theory of diffusive ultrarelativistic photospheres can be applied to this case with great care. In particular, the estimated duration of the thermal signal is only $13Y$ s.

GRB 090618. This burst may represent a canonical case of photon thin outflow launched from the initial radius 10^9 cm with the Lorentz factor $3Y^{-1} < \Gamma < 40Y^{1/4}$. Assuming instantaneous energy injection with $l = R_0$ one finds $Y = 5.7$. The duration of the thermal emission with observed temperature about 1 keV is about $6Y$ s. Note that thermal emission has also been claimed in the prompt phase, with a higher temperature ranging from 54 to 12 keV [41]. Such thermal emission in the prompt phase may be interpreted as a photosphere of the photon thick outflow. Indeed, if the initially high entropy η decreases with time the outflow should experience a transition from photon thick to photon thin case.

GRB 111225A. This case is similar to GRB 060218, but with smaller initial radius of 8.3×10^9 cm and Lorentz factor in the range $1 < \Gamma < 6.0Y^{1/4}$. The duration of the thermal emission with observed temperature of 0.18 keV is about $126Y$ s, with $Y = 2.0$ for $l = R_0$. The lower bound on the Lorentz factor in unconstrained. It may correspond to a cocoon emitting in the diffusive photon thin regime.

GRB 131030A. This case is a typical long burst, similar to GRB 090618, it allows Lorentz factors in the photon thin case in the following range: $4.3Y^{-1} < \Gamma < 66Y^{1/4}$. The duration of the thermal emission with observed temperature of 1.12 keV is about $2.0Y$ s. The initial radius is 3.74×10^8 cm. For instantaneous energy injection $Y = 19$.

GRB 150727A. This case is similar to GRB 111225A with initial radius 1.1×10^9 cm and Lorentz factors in the range $1 < \Gamma < 11Y^{1/4}$, allowing for a photon thin interpretation. The duration of the thermal emission with observed temperature of 0.47 keV is about $191Y$ s, with $Y = 2.1$.

GRB 151027A. This case is similar to GRBs 090618 and 131030, however with quite large initial radius 1.5×10^{10} cm and Lorentz factors in the narrow range $23 < \Gamma < 26Y^{1/4}$. The duration of the thermal emission with observed temperature of 0.96 keV is about $0.47Y$ s, with $Y = 64$.

7. Discussion

The difference between the present work and the approach followed in Ref. [14] should be emphasized. The main assumption of that work is the presence of unknown dissipation mechanism, which transforms part of the kinetic energy of the outflow into radiation, postulated in Ref. [42]. Such dissipation can boost the luminosity of thermal emission and it might be required to explain subdominant thermal component during the prompt emission or even the prompt emission itself, see Ref. [43]. Concerning observations of this component in the early afterglow, dissipation is not required, as it is much weaker than the prompt radiation.

Similarly, there is a difference between the present work and the work in Ref. [15]. There two regimes of expansion are considered: Newtonian ($v < c$) and ultrarelativistic $\eta \gg 1$. For the latter, which is of interest here, the emission was assumed to originate at the photospheric radius, given by the last line in eq. (6). As discussed in Sec. 3 above, photons in this case diffuse out much earlier, so that no photons are left in the outflow when it arrives to the photospheric radius. For this reason estimations of the luminosity and observed temperature in that paper cannot be used.

Qualitative difference in dependence of observed flux and temperature on time for photon thin outflows determine their observed properties. In particular, since the flux up to diffusion time (22) is almost constant and its luminosity is much weaker than the prompt radiation luminosity, see eq. (14), the thermal component become visible after the steep decrease of observed luminosity following the end of the prompt phase. This is indeed where such thermal component is identified in many GRBs. Its disappearance is naturally explained by diffusion of the radiation kept in the outflow. Hence it implies that no more photons are generated neither in the outflow nor in the central engine.

The results of the present work indicate that in several GRBs, namely GRB 060218, 111225A and 150727A, the thermal component observed in the early afterglow may originate from mildly relativistic cocoons emerging from the progenitors together with the jet, due to relatively small values of inferred Lorentz factors $\Gamma < 10$. At the same time, such emission observed in GRBs 090618, 131030A and 151027A correspond to large Lorentz factors $\Gamma > 10$, indicating a jet origin of the photospheric emission. Besides, these results suggest that the progenitors of some long GRBs, in particular GRB 090618 and 131030A could be rather compact objects, with radius $l \sim 10^9$ cm.

It is important to stress that the relatively low temperature of the thermal component observed in the early afterglow with $T \sim 0.1 - 10$ keV, in contrast with typical temperatures detected during the prompt emission with $T \sim 10 - 100$ keV does not indicate small Lorentz factor of the outflow. Conversely, it may point to photospheric origin of the thermal emission in the photon thin regime. Instead, large Lorentz factors $\Gamma \gg 1$ assumed in the model imply small mass of the emitting plasma, which is consistent with the cocoon interpretation [15].

Possible presence of thermal components both in the prompts radiation and in the early afterglow, as well as the presence of breaks in temperature dependence on time found in many cases [44–46] may correspond to the transition from photon thick to photon thin asymptotics in hydrodynamic evolution of the outflow powering GRBs.

8. Conclusions

The theory of diffusive emission from relativistic photospheres is developed and confronted with observational data on a sample of GRBs with thermal component in the early afterglows. The measurement of temperature and flux of the thermal component along with the total flux in the prompt phase are used to determine initial radii of the outflows as well as their Lorentz factors. The results indicate that in several cases (GRBs 060218, 111225A and 150727A) the inferred Lorentz factors are relatively small, $\Gamma < 10$, while in other cases (GRBs 090618, 131030A and 151027A) the inferred Lorentz factors are larger, $\Gamma > 10$. Such differences suggest two possible sources of the thermal component: mildly relativistic cocoons or highly relativistic jets. Results obtained above are valid only for those cases, where inferred Lorentz factor is relatively small, below few tens. For other cases identified in Ref. [11] inferred Lorentz factors are larger, and photon thin interpretation does not apply.

These results are the first indication that radiative diffusion may play an important role not only in nonrelativistic outflows, but also in ultrarelativistic outflows, represented by GRBs.

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