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GRB prompt emission from the synchrotron radiation of relativistic electrons in a decaying magnetic field

Bošnjak, Ž.[a,*] **and Daigne, F.**[b]

[a] *Faculty of Electrical Engineering and Computing, Unska ulica 3, 10000 Zagreb, Croatia*
[b] *Sorbonne Université, CNRS, UMR 7095, 98 bis bd Arago, 75014 Paris, France*

E-mail: Zeljka.Bosnjak@fer.hr, daigne@iap.fr

The origin of the prompt gamma-ray burst (GRB) emission is still highly debated. The observed spectra provide key constraints: the low energy slope of the photon spectrum α, which is commonly determined in energy range of $\sim$ 10 keV up to $\sim$ a few MeV, shows a mean values $\alpha \sim -1$ above the expected value $-3/2$ for the synchrotron fast cooling regime, and even values above $-2/3$, the synchrotron slow cooling limit. We studied the effect of a decaying magnetic field in the emission region on the synchrotron spectrum of relativistic electrons. An important parameter is the timescale for the decay of the magnetic field compared to two other relevant timescales: the dynamical timescale (adiabatic cooling) and the radiative timescale of electrons responsible of the peak of the spectrum. If the magnetic field decay timescale is between these two timescales, our simulation show that the marginally fast cooling regime can be naturally achieved, leading to photon index up to -2/3.

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1. Introduction

The emission mechanism operating during the prompt emission in gamma-ray bursts has been debated for years. The observed spectrum is usually described in the keV/MeV energy band by low- and high-energy power laws, smoothly connected around the peak energy at about $\sim$ a few hundred keV [1]. The low-energy spectral index, α, allows to discriminate between the different radiative processes, while the high-energy spectral index, β is generally related to the slope of the radiating electron distribution. The latest catalogue of GRBs observed by *Fermi* Gamma-Ray Burst Monitor (GBM; [2]) providing the information on spectral parameters on a broad energy range (8 keV - 40 MeV), reported the values for the time-integrated spectral fits $\alpha \sim -1.1$ and high energy spectral index $\beta \sim -2.2$ [3], in consistency with the previous catalogues ([4]; [5]). The time resolved spectral fits [6] performed on the brightest *Fermi* GBM bursts resulted in slightly steeper low energy slopes, $\alpha \sim -0.8$. Recently, alternative fits model were proposed, e.g. [7] proposed a new parametric function (ISSM; Internal Shock Synchrotron Model) inspired by physical model for energy dissipation (e.g. [8]) which can successfully reproduce 81% of the spectra in the GBM bright GRB sample. Several authors used a double smoothly broken power law model to test the presence of the characteristic spectral break at low energies (e.g. [9]; [10]; [11]), finding that the obtained slopes below and above the low energy break were consistent with the prediction of the synchrotron emission. Even if some results of spectral analyses depend on the assumed phenomenological spectral shape, it remains that a significant fraction of GRB prompt spectra have low-energy photon index as high as $-2/3$, or even above, which challenges synchrotron models.

The major models that were proposed to interpret the observed spectral properties at sub-MeV energies include synchrotron radiation from a population of relativistic electrons, and thermal emission arriving from the photosphere when the relativistic flow in which a GRB is produced becomes transparent. The latter may also be reprocessed due to sub-photospheric dissipation processes, where the electrons are heated and become the seeds for inverse-Compton scatterings. The initial Planck spectrum is modified in that case (e.g. [12]; [13]; [14]), and can also appear as non-thermal. If very energetic protons are present in the ejecta following the energy dissipation, the additional spectral components should also be accounted for resulting from the interactions with the locally produced prompt emission photon field (e.g. [15]; [16]; [17]).

Presently there is still no consensus of the prevailing radiative mechanism operating in GRBs. Synchrotron emission is expected as the emission from shock-accelerated electrons in a magnetic field, and is most plausibly at work during the afterglow emission [18]. However, it predicts very soft energy slopes, $\alpha \sim$ - 3/2 in fast cooling regime (that is favoured during the prompt emission due to the high emitted energy requirements). There were several solutions proposed to this problem, e.g. [19], [20] studied the effect of inverse Compton losses in the Klein-Nishina regime and found that values of α between –3/2 and –1 can be reached during the prompt emission. Even steeper slopes, up to –2/3, may be reached in marginally fast cooling regime [19].

The possibility of observing the very-high energy emission (VHE; > 100 GeV) from gamma-ray bursts by e.g. Magic telescopes [21], H.E.S.S. [22] or LHAASO [23], rises the importance of understanding the emission mechanisms at work, in particular the role of inverse Compton scatterings and the possible hadronic component.

2. Synchrotron radiation in a decaying magnetic field

We investigate the possibility of the synchrotron cooling of relativistic electrons in a magnetic field decaying with time. Similar models were explored by e.g. [13], [24], [25] for the prompt emission, and also in the context of afterglows [26]. The idea is that the magnetic field generated in relativistic shock wave decays on a length scale much shorter than the comoving width of the plasma (e.g. [27], [28], [29]). We assume that electrons are accelerated in a region where the magnetic field is B'_0, and reach a power-law distribution with a minimum Lorentz factor $\Gamma_{\rm m}$ and a slope $-p$ (the prime quantities to the values in the comoving frame of the emitting region). Electrons having Lorentz factor γ radiate their energy on the synchrotron timescale,

$$t'_{\rm syn}(\gamma) = t'_{\rm dyn}\frac{\Gamma_{\rm c,0}}{\gamma}\,, \tag{1}$$

where $\Gamma_{\rm c,0}$ is defined as the Lorentz factor of electrons in the magnetic field B'_0 that have a synchrotron timescale equal to the timescale of the adiabatic cooling (dynamical timescale $t'_{\rm dyn}$), i.e.

$$\Gamma_{\rm c,0} = \frac{6\pi\, m_{\rm e}c}{\sigma_{\rm T}\, B'^2_0\, t'_{\rm dyn}}\,. \tag{2}$$

The fast cooling regime ($\Gamma_{\rm m} \gg \Gamma_{\rm c,0}$) implies that all electrons radiate efficiently. If the magnetic field is constant ($B' = B'_0$), the photon index below the peak is $\alpha = -3/2$. A photon index $-2/3$ is recovered only below $\nu'_{\rm c,0} = \nu_{\rm syn}\left(\Gamma_{\rm c,0}\right) = \nu'_{\rm m}\left(\Gamma_{\rm c,0}/\Gamma_{\rm m}\right)^2 \ll \nu'_{\rm m}$. Therefore the standard fast-cooling synchrotron spectrum predicts a low-energy photon index $\alpha = -3/2$ which is lower to what is commonly observed.

A possibility to solve this problem was proposed by [19]: in the *marginally fast cooling* regime, where the cooling break $\nu'_{\rm c,0}$ is very close to the peak $\nu'_{\rm m}$, the intermediate region of the spectrum with slope $-3/2$ becomes negligible and the large value $\alpha = -2/3$ is recovered. However, maintaining the condition of marginally fast cooling during the course of the prompt GRB emission may require some kind of fine-tuning of the microphysics parameters. This regime can however naturally emerge if electrons are radiating in a decaying magnetic field.

We considered the case where the magnetic field decays outside the acceleration site over a timescale $t'_{\rm B}$. An electron escaping the acceleration site will radiate in the decaying magnetic field. Electrons with Lorentz factor $\gamma \geq \Gamma_{\rm m}$ will still experience a magnetic field B'_0 and the peak and the high-energy part of the synchrotron spectrum will not be affected. On the other hand, if $t'_{\rm B} < t'_{\rm dyn}$, the electrons with Lorentz factors $\Gamma_{\rm c,0} < \gamma < \Gamma_{\rm m}$ will lose their energy more slowly than expected because they will encounter a lower magnetic field when they start to travel outside the initial acceleration site. This will affect the low-energy part of the synchrotron spectrum, as the cooling break will increase to $\nu_{\rm c} \simeq \nu_{\rm c,0}\left(t'_{\rm dyn}/t'_{\rm B}\right)^2$. This allows to naturally tend towards the marginally fast cooling regime.

The radiative efficiency will remain high as long as $t'_{\rm B} \gg t'_{\rm syn}(\Gamma_{\rm m})$, i.e. $t'_{\rm B}/t'_{\rm dyn} \gg \Gamma_{\rm c,0}/\Gamma_{\rm m}$. This leads to the final condition for the regime we investigate:

$$\frac{\Gamma_{\rm c,0}}{\Gamma_{\rm m}} \lesssim \frac{t'_{\rm B}}{t'_{\rm dyn}} \lesssim 1 \tag{3}$$

Note that if the magnetic field decays extremely fast ($t'_{\rm B}/t'_{\rm dyn} < \Gamma_{\rm c,0}/\Gamma_{\rm m}$), the low-energy photon index $\alpha = -2/3$ is still recovered, but all electrons may be slow cooling, leading to a lower radiative efficiency. On the other hand, if $t'_{\rm B}/t'_{\rm dyn} > 1$, the observed spectrum is mostly unaffected by the magnetic field decay.

3. Results

We explore the mechanism described above by assuming a simple prescription for the magnetic field decay:

$$B'(t') = B'_0\, e^{-t'/t'_{\rm B}}\,. \tag{4}$$

while [30], [26] rather considered a power-law decay of the magnetic field. We also tested such a prescription and this does not change significantly our conclusions. Therefore we only consider exponential decay in the following, as it introduces a single new parameter, the timescale $t'_{\rm B}$, rather than two parameters in the case of a power-law. The electrons radiate efficiently only above an effective Lorentz factor

$$\Gamma_{\rm c,eff} \simeq \frac{t'_{\rm dyn}}{t'_{\rm B}}\Gamma_{\rm c,0}\,, \tag{5}$$

which leads to an increase of the cooling break frequency by a factor $\left(t'_{\rm dyn}/t'_{\rm B}\right)^2$, as described above. We note that for an extreme decay, i.e. $t'_{\rm B}/t'_{\rm dyn} \ll \frac{\Gamma_{\rm c,0}}{\Gamma_{\rm m}}$, we expect a slow cooling spectrum even for $\Gamma_{\rm m} > \Gamma_{\rm c,0}$. We show the effect of a decaying magnetic field on the synchrotron spectrum in Fig. 1., using the following parameters: $\Gamma_{\rm c,0} = \Gamma_{\rm m}/300$, $Y_{\rm Th} = 10$, $w_{\rm m} = 10^2$, $p = 2.5$. For the constant magnetic field, we obtain the standard fast cooling synchrotron spectrum [18], with a photon index α = –3/2 below the spectral peak. For the decaying magnetic field, the effective cooling break becomes $\nu'_{\rm c} = \nu'_{\rm c,0}\left(t'_{\rm dyn}/t'_{\rm B}\right)^2 \sim 10^4\,\nu'_{\rm c,0}$, so that the intermediate spectral region disappears and the photon index α = -2/3 is measured below the peak.

The inverse Compton scatterings can also strongly affect the cooling of electrons. [8]; [19] demonstrated that the effect on the synchrotron spectral component is determined by two parameters:

$$w_{\rm m} = \Gamma_{\rm m}\frac{h\nu'_{\rm m}}{m_{\rm e}c^2}\,, \tag{6}$$

which measures if scatterings occur mostly in Thomson regime ($w_{\rm m} \ll 1$) or if Klein-Nishina corrections are important, and

$$Y_{\rm Th} = \frac{4}{3}\Gamma_{\rm m}^2\left(\sigma_{\rm T}\, n_{\rm e}^{\rm acc}\, ct'_{\rm syn}\left(\Gamma_{\rm m}\right)\right), \tag{7}$$

which governs the efficiency of scatterings. It was shown that for $Y_{\rm Th} \gg 1$ and $w_{\rm m} \gg 1$, a photon index $\alpha \lesssim -1$ is obtained below $\nu'_{\rm m}$ in the synchrotron component [19]. Implementing the Eq. (4) in a radiative code described in [8], we calculated the evolution of the distribution of electrons, and the corresponding emitted spectrum, in the case where inverse Compton scatterings are taken into account. This is done for the same example in Fig. 1, using $Y_{\rm Th} = 10$ and $w_{\rm m} = 100$ (red curves). For comparison, the synchrotron only case is also plotted with the same radiative code (black line).

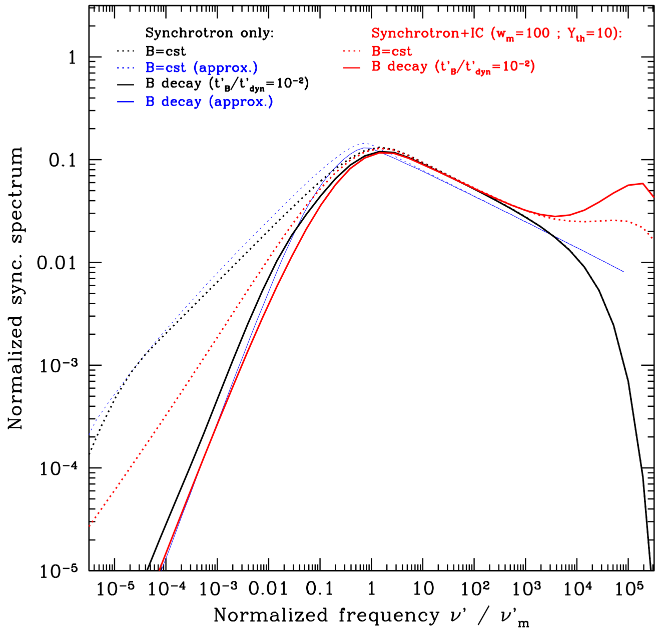

Figure 1: Effect of a decaying magnetic field on the synchrotron spectrum. The normalized spectrum $\nu' u_{\nu'}/u_\mathrm{e}$ is plotted as a function of the normalized frequency ν'/ν'_m for a constant magnetic field (dotted line) or a decaying magnetic field on a timescale $t'_\mathrm{B} = 10^{-2} t'_\mathrm{dyn}$ (solid line). The calculation is done with the numerical radiative code, either including only the synchrotron process (black) or both the synchrotron radiation and the inverse Compton scatterings (red). From Daigne & Bošnjak 2023, in preparation.

We see that when inverse Compton scatterings are taken into account, a steeper slope is found in case of a constant magnetic field (due to the effect of scatterings in Klein-Nishina regime). An even steeper slope is obtained when the decay of magnetic field is included.

As in gamma-ray bursts there are several emission zones with possible different physical conditions, the spectral evolution is expected. To simulated the predicted spectral evolution, we need a dynamical model for the emission regions and their evolution. We illustrate in Fig. 2. the results obtained in the internal shock model, for reference case B as described in [8]. This reference case was produced using the following parameters: Lorentz factor of the flow varying gradually between 100 and 400, dE/dt = 5×10^{53}ergs/s, $\epsilon_B = 5 \times 10^{-3}$, $\epsilon_e = 1/3$, $\zeta = 2 \times 10^{-3}$ and $p = 2.5$. We included in our calculation the assumption $t'_\mathrm{B}/t'_\mathrm{dyn} = 10^{-2}$. Indeed, the low energy slopes of the spectrum become steeper than –1, and the evolution is deteremined by the parameters shown in top panel, w_m, Y_Th and $\Gamma_{\mathrm{c},0}/\Gamma_\mathrm{m}$.

4. Conclusions

The low energy spectral slope offers a valuable information about the radiative processes at work during the prompt emission. We studied the effect of synchrotron cooling of relativistic electrons in a decaying magnetic field on the spectrum, based on the recent findings of particle acceleration simulations in different settings relevant for gamma-ray bursts. Our simulations show

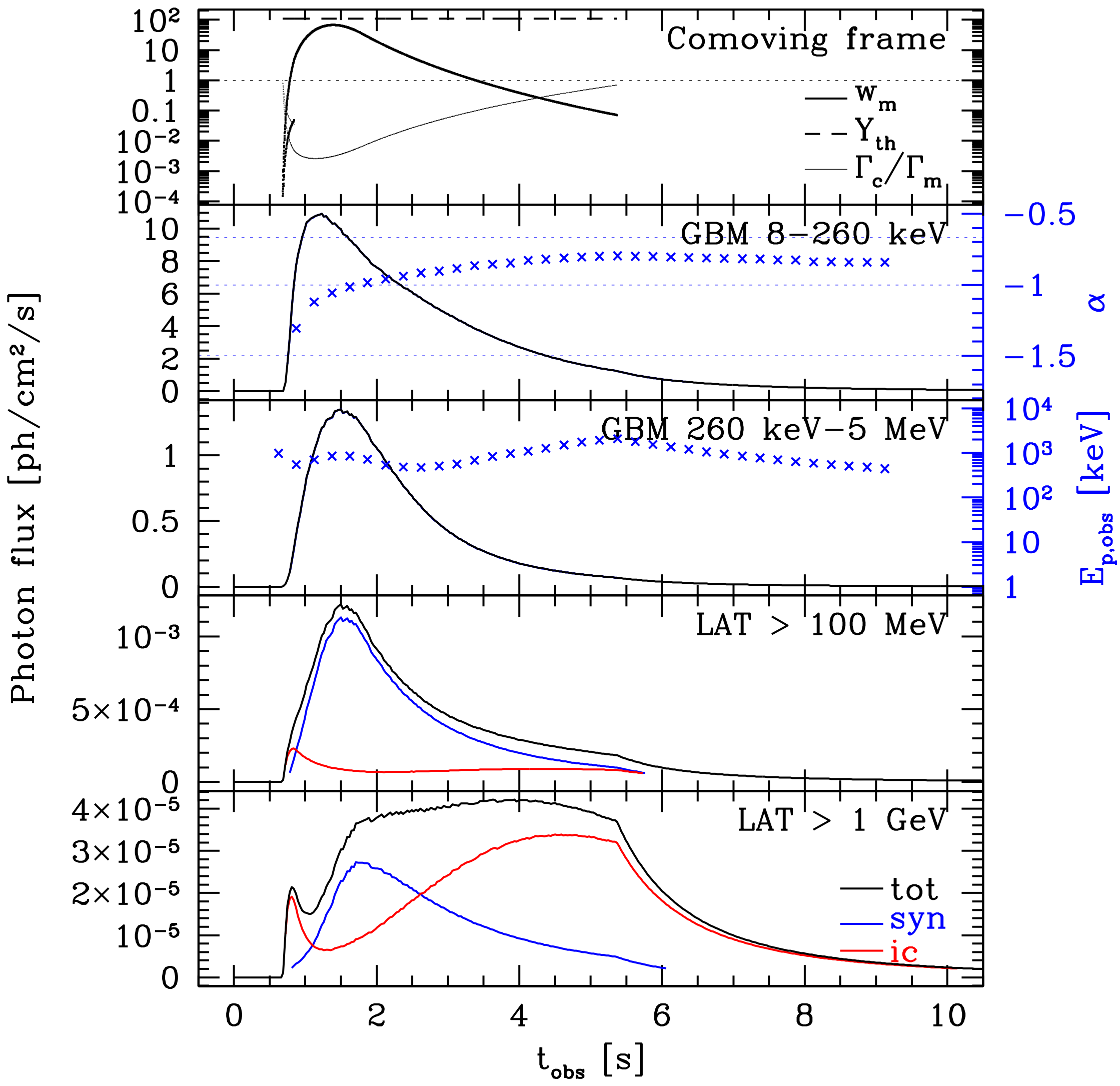

Figure 2: Effect of a decaying magnetic field in the internal shock model with $t'_B/t'_{dyn} = 10^{-2}$. Different panels show lightcurves in the GBM and LAT range. The top panel shows the evolution of the parameters w_m, Y_{Th} and $\Gamma_{c,0}/\Gamma_m$ in the comoving frame of the shocked material.

that the steep low energy slopes can be achieved for $\Gamma_{c,0}/\Gamma_m \leq t'_B/t'_{dyn} \leq 1$ where the regime of marginally fast cooling is naturally achieved.

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