

Gamma-ray burst spectra from continuously accelerated electrons^(*)

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Summary. — We discuss here constraints on the particle acceleration models from the observed gamma-ray bursts spectra. The standard synchrotron shock model assumes that some fraction of available energy is given instantaneously to the electrons which are injected at high Lorentz factor. The emitted spectrum in that case corresponds to the spectrum of cooling electrons, $F_\nu \propto \nu^{-1/2}$, is much too soft to account for the majority of the observed spectral slopes. We show that continuous heating of electrons over the life-time of a source is needed to produce hard observed spectra. In this model, a prominent peak develops in the electron distribution at energy which is a strong function of Thomson optical depth τ_T of heated electrons (pairs). At $\tau_T \gtrsim 1$, a typical electron Lorentz factor $\langle \gamma \rangle \sim 1-2$ and quasi-thermal Comptonization operates. It produces spectrum peaking at a too high energy. Optical depths below 10^{-4} would be difficult to imagine in any physical scenario. At $\tau_T \approx 10^{-4}-10^{-2}$, $\langle \gamma \rangle \sim 30-100$ and synchrotron self-Compton radiation is the main emission mechanism. The synchrotron peak should be observed at 10–100 eV, while the self-absorbed low-energy tail with $F_\nu \propto \nu^2$ can produce the prompt optical emission (like in the case of GRB 990123). The first Compton scattering radiation by nearly monoenergetic electrons peaks in the BATSE energy band and can be as hard as $F_\nu \propto \nu^1$ reproducing the hardness of most of the observed GRB spectra. The second Compton peak should be observed in the high-energy gamma-ray band, possibly being responsible for the 10–100 MeV emission detected in GRB 941017. A significant electron-positron pair production reduces the available energy per particle, moving spectral peaks to lower energies as the burst progresses.

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1. – Introduction

The time-resolved gamma-ray burst (GRB) spectra have the mean observed photon spectral index α close to -1 (*i.e.* $F_\nu \propto \nu^0$) and some spectra can be as hard as $F_\nu \propto \nu^1$ [9]. Synchrotron shock models (see, *e.g.*, [8]) assume that a fraction of the available energy is given instantaneously to the electrons which are injected at Lorentz factor $\gamma \gtrsim 10^3$. The typical cooling time-scale is smaller than the light crossing time of the source by a factor $\gamma\ell$, where the compactness ℓ is about 0.1–10 for typical GRB parameters [12]. Because the cooling time is small, one observes the time-averaged spectrum of cooling electrons [3, 4].

For relativistic electrons, the photon emission frequency is $\nu \propto \gamma^m$, where $m = 2$ for synchrotron or synchrotron-self-Compton (SSC) radiation, respectively. Thus, the rate of the frequency change $d\nu/dt \propto \gamma^{m-1}d\gamma/dt \propto \gamma^{m-1}P \propto \nu^{(m-1)/m}P$, where $P = dE/dt$ is the emitted power. The time-averaged flux is then

$$(1) \quad F_\nu = \frac{dE}{d\nu} = \frac{dE}{dt} \frac{dt}{d\nu} = \frac{P}{d\nu/dt} \propto \nu^{-(m-1)/m},$$

and the “cooling” spectrum is $F_\nu \propto \nu^{-1/2}$ (*i.e.* $\alpha = -3/2$) for synchrotron as well as for SSC [4], which is much softer than those observed from GRBs. The immediate conclusion from this simple exercise is that *all* the models involving injection of electrons at large energies should be rejected.

The efficient cooling can be prevented if the energy is supplied to the electrons in small steps. In this paper, we discuss consequences of the assumption that the available energy is supplied continuously to the particles over the life-time of a source. We study how the resulting spectrum depends on main parameters and determine parameter range where model spectra are consistent with the majority of the observed ones.

2. – Spectra from continuously heated electrons

2.1. Model setup. – A number of physical models can produce a source of continuously heated particles. These can be plasma instabilities behind ultrarelativistic shocks [7] or dissipation of the magnetic energy in a Poynting flux dominated outflow (*e.g.*, [5]). Therefore, we consider a toy model where energy is injected to the emission region with the constant rate during comoving time R'/c . We adopt a slab geometry with the thickness $\Delta = 0.1$ (in units of R') which may depend on the specific scenario. The energy is injected uniformly over the slab volume in a form of acceleration of electrons (and pairs) which obtain equal amount of energy per unit time. The model is fully described by four parameters: i) the initial Thomson optical depth across the slab, $\tau_0 = n_e\sigma_T\Delta R'$; ii) the comoving size R' ; iii) the dissipation compactness, $\ell = E_{\text{rad}}\sigma_T/(m_e c^2 \Gamma^3 4\pi R'^2)$ related to the observed isotropic energy release E_{rad} and the ejecta bulk Lorentz factor Γ , which determines the rate of pair production; and iv) the magnetic compactness $\Lambda_B = B^2 R' \sigma_T / (8\pi m_e c^2)$ determining the role of synchrotron radiation. See [12] for details.

2.2. Radiative processes. – Let us first consider how particles (electron and positrons) of Lorentz factor γ are heated and how do they cool. The energy gain rate of a particle is simply given by the heating rate $\propto \ell$ divided by the number of particles (which is proportional to the total Thomson optical depth, including pairs, across the slab, τ_T). Particles cool by emitting synchrotron radiation and by scattering this radiation (SSC). The energy balance equation can be written as

$$(2) \quad \frac{d\gamma}{dt'} = \frac{\ell}{\tau_T} - \frac{4}{3}(\eta\Lambda_B + \Lambda_T)\gamma^2,$$

where $\eta < 1$ accounts for the reduced synchrotron cooling due to synchrotron self-absorption and Λ_T is the compactness corresponding to the energy density of soft photons in the Thomson regime. It can be expressed as a sum of the synchrotron $\Lambda_s = y\eta\Lambda_B$ and first Compton scattering $\Lambda_c = y\eta\Lambda_s$ energy densities, where $y \approx \tau_T \langle \gamma^2 \rangle$ is the Compton parameter. If mean Lorentz factor $\langle \gamma \rangle \lesssim 10$, then one needs to account for further scattering orders. The typical cooling time, $t_{\text{cool}} \sim (R'/c)/[(\Lambda_T + \eta\Lambda_B)\gamma]$, is orders of magnitude smaller than the light-crossing time R'/c for GRB conditions.

The balance between heating and cooling is achieved at

$$(3) \quad \gamma_b \approx \sqrt{\ell/(\Lambda_T + \eta\Lambda_B)}\tau_T^{-1/2} \approx \text{a few} \times \tau_T^{-1/2},$$

and thus $y = \text{a few}$. Particles with $\gamma > \gamma_b$ lose energy faster than they gain it, while at $\gamma < \gamma_b$ the situation is opposite resulting in a narrow distribution peaked at γ_b .

Main radiative process is determined by the instantaneous optical depth τ_T , which can be significantly larger than the initial τ_0 because of pair production at $\ell \gtrsim 0.1$. If $\tau_T \lesssim 10^{-8}$, then $\gamma_b \gtrsim 10^4$ and the main emission mechanism is synchrotron. A typical energy of a synchrotron photon in the frame comoving with the ejecta (in units $m_e c^2$) is $\epsilon_s \approx b\gamma_b^2 \sim 1$, for $b \sim 10^{-8}$ (where $b = B/B_{\text{QED}}$ and $B_{\text{QED}} = 4.4 \times 10^{13}$ G) and Compton scattering is in Klein-Nishina limit.

If $\tau_T \sim 10^{-4}$, $\langle \gamma \rangle \sim 10^2$ and $\epsilon_s \sim 10^{-4}$. This time, first Compton scattering peak is at $\epsilon_{c1} \sim 1$, and one can neglect further scatterings. At $\tau_T \sim 10^{-2}$ – 10^{-3} , second Compton scattering will dominate the energy output. For high compactness source τ_T can reach 1, then $\langle \gamma \rangle \sim 1$ – 2 and multiply Compton scatterings (quasi-thermal Comptonization) have to be accounted for.

2.3. Simulations. – The simulations were performed using a Large Particle Monte Carlo code described in [13]. It treats Compton scattering, photon-photon pair production and pair annihilation, synchrotron radiation and synchrotron self-absorption. The electron/pair and photon distributions are computed self-consistently.

As an example, we consider $R' = 10^{13}$ cm, $\tau_0 = 6 \times 10^{-4}$, $\ell = 3$ (corresponding to $\Gamma \approx 130$ and $E_{\text{rad}} = 10^{52}$ erg), and $\Lambda_B = 0.3$, which are typical for GRB ejecta [12]. The resulting evolution of broad-band photon spectra and electron distributions is shown in fig. 1. At the start of simulations $\tau_T = \tau_0$ and $\langle \gamma \rangle \sim 80$ (see dashed curves). Partially self-absorbed synchrotron peaks at $\epsilon_s \sim 3 \times 10^{-7}$ (UV in the observer frame) with low-energy tail $F_\nu \propto \nu^2$ may be responsible for the prompt optical emission seen in GRB 990123 [1]. When τ_T starts to grow due to pair production, $\langle \gamma \rangle$ drops as $1/\sqrt{\tau}$, and the first Compton peak moves to softer energies crossing the “BATSE window”. This spectral evolution is consistent with the observed in time-resolved pulses [2, 10]. The low-energy slope of this component, corresponding to Compton scattering by isotropic monoenergetic electrons, can as hard as $F_\nu \propto \nu^1$ (*i.e.* $\alpha = 0$), reproducing most of the observed GRB spectra. The second Compton component peaking at ~ 10 – 100 MeV rises later and decays on a longer time-scale. It can be responsible for the delayed emission observed by EGRET from GRB 941017 [6]. Thus, at $\tau_T \sim 10^{-2}$ – 10^{-4} , the model spectra reproduce well the observed ones from GRBs, including their hardness, spectral evolution, as well as optical and 100 MeV emission.

Small τ_T required for synchrotron to be responsible for the BATSE GRBs are difficult to get in any physical scenario. Additionally, the synchrotron low-energy spectrum

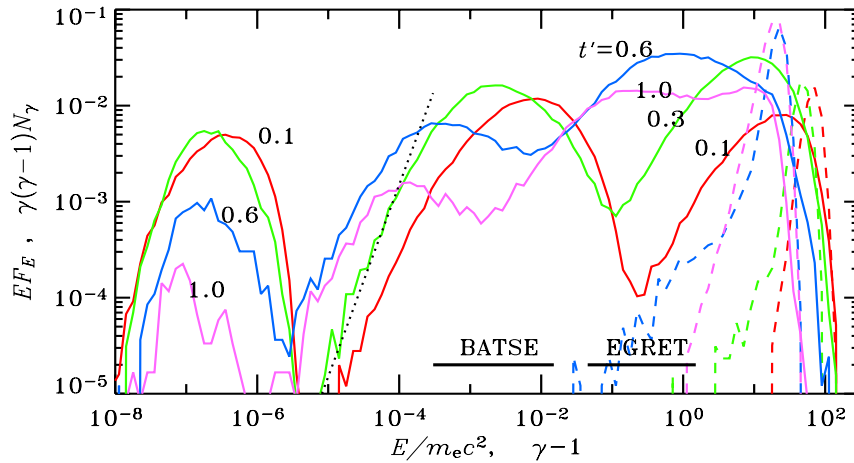


Fig. 1. – Instantaneous (comoving frame) photon spectra (solid curves) and corresponding electron distributions (dashed) at times of 0.1, 0.3, 0.6, and 1 (in units R'/c). The spectra consist of a low-energy synchrotron and two Compton scattering orders. The hardest possible power law $F_\nu \propto \nu^1$ reachable at the low-energy slope of the first Compton bump is shown with dotted line. The BATSE (20–1000 keV) and EGRET (3–100 MeV) bands (redshifted to a comoving frame) are marked.

$F_\nu \propto \nu^{1/3}$ is softer than the observed ones [9]. At $\tau_T \gtrsim 1$, the resulting quasi-thermal Comptonization spectrum may be too soft for most of the GRB spectra. The emission peaks at 10–50 keV in the comoving frame of the ejecta and, for $\Gamma \sim 100$, this peak shifts to an uncomfortably high energy [3, 11, 12]. In conclusion, SSC from continuously heated electrons (pairs) seems to be the most promising model to explain the observed properties of GRBs.

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REFERENCES

- [1] AKERLOF C. *et al.*, *Nature*, **398** (1999) 400.
- [2] FORD L. A. *et al.*, *ApJ*, **439** (1995) 307.
- [3] GHISELLINI G. and CELOTTI A., *ApJ*, **511** (1999) L93.
- [4] GHISELLINI G., CELOTTI A. and LAZZATI D., *MNRAS*, **313** (2000) L1.
- [5] GIANNIOS D. and SPRUIT H. C., *A&A*, **430** (2005) 1.
- [6] GONZÁLEZ M. M. *et al.*, *Nature*, **424** (2003) 749.
- [7] HEDEDAL C. B. *et al.*, *ApJ*, **617** (2004) L107.
- [8] PIRAN T., *Phys. Rep.*, **314** (1999) 575.
- [9] PREECE R. E. *et al.*, *ApJS*, **126** (2000) 19.
- [10] RYDE F. and SVENSSON R., *ApJ*, **566** (2002) 210.
- [11] STERN B. E., in *High Energy Processes in Accreting Black Holes*, edited by POUTANEN J. and SVENSSON R., *ASP*, Vol. **161** (ASP, San Francisco) 1999, pp. 277–291.
- [12] STERN B. E. and POUTANEN J., *MNRAS*, **352** (2004) L35.
- [13] STERN B. E. *et al.*, *MNRAS*, **272** (1995) 291.