GRB spectral parameters within the fireball model

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274 IAU Symposium, Advances in Plasma Astrophysics, Giardini-Naxos, ITALY, 6-10 Sept. 2010

Abstract

Fireball model of the GRBs predicts generation of numerous internal shocks, which then efficiently accelerate charged particles and generate magnetic and electric fields. These fields are produced in the form of relatively small-scale stochastic ensembles of waves, thus, the accelerated particles diffuse in space due to interaction with the random waves and so emit so called Diffusive Synchrotron Radiation (DSR) in contrast to standard synchrotron radiation they would produce in a large-scale regular magnetic fields. Here we present modeling of the GRB spectral parameters within the fireball/internal shock concept. We have found that the non-perturbative DSR emission mechanism in a strong random magnetic field is consistent with observed distributions of the Band parameters and also with cross-correlations between them; this analysis allowed to restrict GRB physical parameters from the requirement of consistency between the model and observed distributions.

INTRODUCTION

The fireball model is currently accepted as a standard model of the gamma-ray burst (GRB) prompt emission. It is supposed that a central engine produces a number of relativistic internal shocks, which then interact with each other. The phenomenon of the shock waves requires an efficient mechanism of energy dissipation. In a collisionless case, the most efficient ways of the energy dissipation are via generation of fluctuating electromagnetic fields and acceleration of charged particles up to high energies.

Microscopically, this field generation can be driven by two-stream instabilities associated with the shock propagation, while the acceleration of particles is provided by their interaction with the shock-generated random and regular electromagnetic fields. It is well established by now that the magnetic and electric fields produced in the shock interactions have often a significant random component at various spatial scales. The presence of the random component is critically important for generation of non-thermal emission from corresponding objects. Indeed, unlike regular gyration in the presence of a regular magnetic field, the shock-accelerated charged particles moving through a plasma with random electromagnetic fields experience random Lorenz forces and so follow random trajectories representing a kind of spatial diffusion. Accordingly, the particles produce a diffusive radiation whose spectra depend on the type of the field (magnetic or electric) and on spectral energy distribution of the field over the spatial scales.

Individual spectra of the prompt GRB emission are typically well fitted by a phenomenological Band function (Band et al. 1993), which consists of low-energy (spectral index α) and high-energy (spectral index β) power-law regions smoothly linked at a break energy Ebr. The DSR was shown (Fleishman 2006) to produce spectra consistent with those observed typically from the GRBs (Band et al. 1993; Mazets et al. 2004; Ohno et al. 2008; Pal'shin et al. 2008; Granot et al. 2009). It had yet been unclear, however, if the DSR spectra are naturally consistent with observed distributions of the GRB spectral parameters (Preece et al. 2000; Kaneko et al. 2006) and what ranges of physical GRB parameters are needed to reconcile the theoretical spectra with the observed ones. In this poster we present a model of GRB prompt emission generation by DSR in relativistically expanding GRB jets. The input parameters of the model are constrained by available observations and take into account dependences between involved parameters implied by physical laws. We vary a number of free parameters of the model to achieve the best agreement between the variety of the modeled and observed spectra. This analysis confirms that the DSR model, specifically the non-perturbative strong-field regime, is intrinsically consistent with the observed distributions of the GRB spectral parameters.

FORMULATION OF THE MODEL

To be specific we adopt the fireball model in which the GRB prompt emission is generated in a collimated jet ejected with a relativistically high speed v from a central engine. Adopting a general internal shocks/fireball concept we accept that a single binary collision of relativistic internal shocks results in a single episode of the GRB prompt emission. Microscopically, this shock–shock interaction first produces high levels of random magnetic and/or electric fields and accelerates the charged particles up to large ultrarelativistic energies; and then these particles interact with the random fields to generate the gamma-rays. Although there are some common general properties of all cases of relativistic shock interactions, each shock–shock collision is, nevertheless, unique in terms of combination of the physical parameters involved. Accordingly, we are going to estimate and adopt a set of standard ('mean') parameters appropriate to account for the most global GRB properties, and then consider if a reasonable scatter of those standard parameters is capable of reproducing more detailed properties of the considered class of events as a whole – the statistical distributions of the GRB spectral parameters and cross-correlations between them. To do so, we consider a number of different emission models including the standard synchrotron radiation and DSR regimes in case of either weak or strong random magnetic field. The spectral slopes and breaks depend on both the emission mechanism and combination of physical parameters affecting the radiation spectra within a given mechanism. Thus, the goal of the modeling is to establish if there exists a parametric space making one or another theoretical model compatible with the observational data on the GRB spectral properties.

Although synchrotron models are generally consistent with overall GRB energetics and light curves, they are intrinsically incompatible with the distribution of low-energy spectral index α (e.g. Baring & Braby 2004). To demonstrate this explicitly, we show the model distribution of the low-energy indices obtained within a synchrotron model in Fig. 1. To be specific in generating this histogram we assumed the slow cooling regime and reasonable statistical distributions of the relevant parameters (see below for greater detail), such as bulk Lorentz factor of the relativistically expanding shell, energy content of the accelerated particles and produced magnetic field, number density of the particles and their energy spectrum, as well as correlations between these parameters consistent with observations (M´esz´aros 2006; Sari 2006). The histogram in Fig. 1, representing an asymmetric narrow distribution peaking around $\alpha = -0.7$, is in evident contradiction with the observed one (Preece et al. 2000; Baring & Braby 2004; Kaneko et al. 2006), which is a more or less symmetric broad distribution peaking at $\alpha \approx -1$. The fast cooling regime results in a histogram similar to that in Fig. 1 with the only difference that it peaks around $\alpha \approx -1.5$. We conclude that a more sophisticated modeling is needed to achieve reasonable agreement between the observations and the theory of electromagnetic emission in the GRB sources. To address this problem, Medvedev (2000) proposed that emission of fast electrons moving in *small-scale* random magnetic field may possess the spectral properties consistent with those observed from GRBs; the corresponding DSR process in the GRB context has than been studied quantitatively by Fleishman (2006) within general concept of the stochastic theory of radiation proposed by Toptygin & Fleishman (1987).

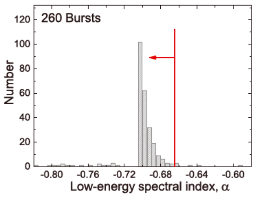


Figure 1. **Model histogram of the spectral index distribution assuming slow cooling synchrotron regime. Note that most of the indices are displaced by a small value compared with the asymptotic value, −2/3 (the 'line of death'). There are a number of outliers with a few of them apparently violating the 'line of death'. These outliers originate from the fit errors provided that the Band fitting function does not represent a perfect match to the theoretical synchrotron spectrum.**

Dependences of the DSR spectrum on the input parameters

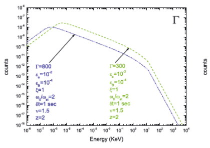


Figure 2. Change in the DSR spectrum due to bulk Lorenz factor Γ change.

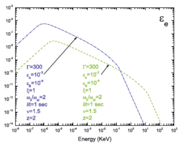


Figure 3. Change in the DSR spectrum due to ϵ_e change.

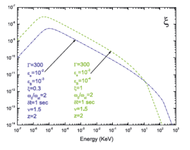


Figure 6. Change in the DSR spectrum due to ξ_e change.

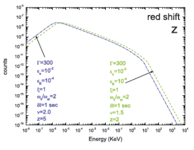


Figure 7. Change in the DSR spectrum due to z change.

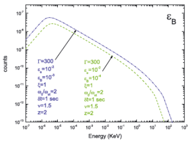


Figure 4. Change in the DSR spectrum due to ϵ_B change.

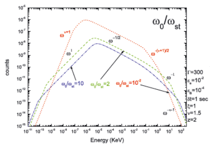


Figure 5. Change in the DSR spectrum due to $\Lambda = \omega_0/\omega_{st}$ change.

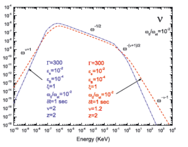


Figure 8. Change in the DSR spectrum due to ν change.

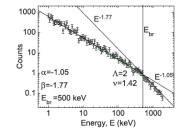


Figure 9. Example of the model noisy DSR spectrum (symbols) and fitting Band spectrum (solid thick green line).

MODELING RESULTS

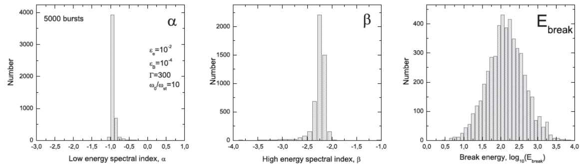
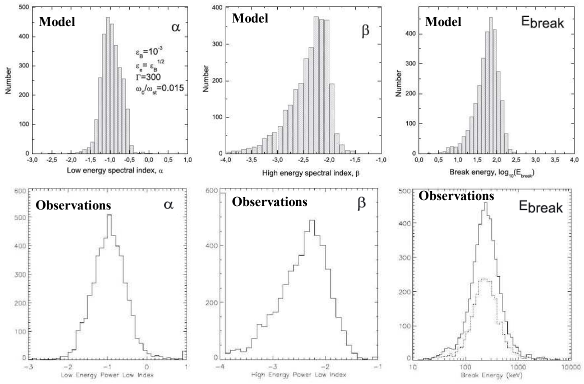


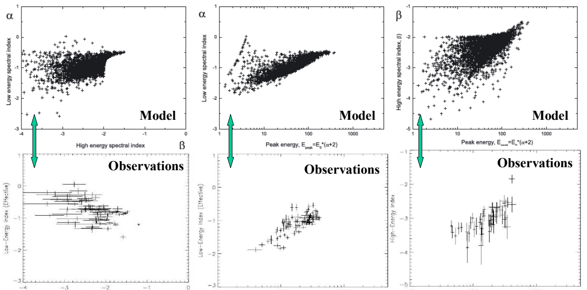
Figure 10. Histograms of the Band parameters α, β and $E_{\rm break}$ obtained within the perturbative (jitter) DSR model assuming the random magnetic field is weak.

Fig. 10 displays the model histograms in the perturbative (jitter) DSR regime. Remarkably, the model Ebreak histogram is very similar to the observed one, while the α and β histograms display the peak values consistent with the observed ones (−1 and −2.2, respectively), although the widths of the model histograms are much smaller than of the observed ones. This inconsistency can be related to (i) use of the simplified perturbative treatment, (ii) non-optimal parameter range or (iii) fundamental shortage of the adopted DSR model. We, thus, address these issues by applying full non-perturbative DSR treatment and exploring more complete range of the involved parameters. Having the weak random field model (jitter regime) rejected, we turn now to analysis of the strong random field case, $\Lambda = \omega_0/\omega_{st} \le 1$. As has been explained, new asymptotes arise in this case, which can yield broader α distribution if this new regime comes into play. Therefore, the model α distribution will depend on adopted ν distribution, which is in fact unconstrained by the observations. However, we can take advantage of the fact that in our model the β distribution is straightforwardly determined by the ν distribution. Indeed, because $\beta = -\nu - 1$, we can simply derive the required ν distribution from the observed β distribution. The model results are in a remarkable agreement with the observations. Indeed, the α histogram is a symmetric one, it displays a peak at the right place, $\alpha = -1$, and its bandwidth is comparable to that of the observed histogram. The β histogram almost repeats the observed one, displaying the correct asymmetric shape and the peak at the right place, $\beta = -2.2$. The Ebreak histogram agrees with the observed one rather well: it has correct shape and bandwidth, although the peak value is less than the observed value by the factor around 2.



Cross-correlations between the model Band parameters

These cross-correlations (top panels) are to be compared with fig. 31 from Kaneko et al. (2006) (bottom panels). Like in the observation, the spectral indices α and β are not highly correlated, although in the model plot the region of −0.5 < α < 0 is underpopulated compared with the observed plot (Kaneko et al. 2006). Two other plots are in remarkable agreement with the observed cross-correlation plots, presented in Kaneko et al. (2006). We conclude that the developed model is naturally capable of reproducing the cross-correlation plots in addition to the histograms themselves, which is a remarkable success of the ***non-perturbative DSR*** model in the presence of ***strong random magnetic field***.



Summary

Our modeling shows that we can get an overall agreement between the model and observed histograms of the Band GRB spectral parameters within the non-perturbative DSR model with strong random magnetic field when ω0/ωst ≈ 0.015. The histogram of the ω0/ωpe ratio obtained for the model with ω0/ωst = 0.015 is show in the last Figure. The distribution has a symmetric bell shape with the peak about 0.5, thus, Lmax ≈ 4πl_{sc} and the required random field correlation length is indeed of the order of 10 plasma skin scales, which agrees with the idea of the random field generation by a two-steam instability in the internal shock interactions.