Spectral Modeling of GRB Pulses

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Abstract. The energy spectra of pulses of GRBs are modeled for synchrotron and multiple self-inverse Compton scatterings from a population of thermal and non-thermal $e^-$s. The contribution from pairs that result from annihilation is also taken into account. A high particle density (enhanced by the pairs) will increase absorption but, if the pairs are not accelerated, the absorption frequency cannot lie in the BATSE window. Pairs will contribute in upscattering and will most likely increase the population of cold particles that will downscatter hard photons and thus suppress hard (e.g., above 300 keV) emission.

INTRODUCTION

The properties of time resolved BATSE spectra can probe the actual physical mechanisms responsible for the emission in this range. Time integrated spectra, on the other hand, result from the integration of time-dependent quantities which tends to smooth out spectral features. In the case of GRBs, such an averaging is unavoidable due to the photon time delay and aberration inherent in a relativistically moving medium. Spectral evolution sequences or average spectra over the course of the whole burst will reflect the hydrodynamical evolution of the quantities involved in the radiation processes. Quantities like the bulk Lorenz factor $\Gamma_b$ of the flow, or the available energy, will remain roughly constant during the generation of a pulse. Therefore, spectral modeling of pulses addresses best the radiative mechanisms. Spectral fits of a large number of bright time-resolved spectra [1] have furnished distributions of the three main spectral parameters: the low ($\alpha$) and high ($\beta$) photon spectral indices and the frequency of the spectral break ($E_b$). These quantities are primarily linked with the emission processes. The surprising narrow $E_b$ distribution probably holds the key answer to the physical mechanisms (be them the radiation process itself, or the mechanism for magnetic field amplification and particle acceleration). In the widely used synchrotron self-inverse Compton model for GRB spectra, $E_b$ is a function of free parameters and can only be used to constrain them [2].

The low energy spectral index $\alpha$ has a distribution [1] that can be approximated by a Gaussian centered at $\alpha = -1$, with a FWHM of $\sim 0.9$ plus a separate com-
ponent of a small percentage of cases with $\alpha = 1$. The radiative mechanisms that would *intrinsically* result in these values are: Comptonization by moderate optical depth [3], or bremsstrahlung in $\alpha \approx -1$, optically thin synchrotron from a (cooled) electron power law in $\alpha = -2/3(-3/2)$, inverse Compton (IC) in $\alpha = 0$, optically thick emission by any mechanism in the Rayleigh-Jeans limit in $\alpha = 1$. More importantly, any steep intrinsic spectral slope portion of the spectrum will be observed flatter due to sampling over volume, energy, time distributions (e.g., a self absorbed synchrotron spectrum with the self-absorption frequency, $\nu_{\text{abs}}$, sweeping through the window of interest due to an increase in the thickness of the medium will result in a photon index of 1, rather than 1.5 [4]). Further inferred flattening of the value of $\alpha$ is introduced when fitting a spectrum through model broadband functions because, in practice, the BATSE window is too narrow [1], [5]. The large number of cases with $\alpha > -2/3$, coined as the “death line of the synchrotron model” [6], suggests that any model employed will not be in a fully optically thin regime in the BATSE window.

The high energy power law index $\beta$ provides the best indication for the acceleration of particles to a power law (of index $p$). The distribution of the fitted values in the time resolved sample [1] is bimodal, its main component peaking at $\beta \approx -2.25$. If interpreted as synchrotron emission from particles that have cooled down, it gives $p = 2.5$. This is in agreement with the values derived from afterglows and is reproduced by particle acceleration calculations [7]. Attributing the full range of $\beta$ values to synchrotron emission from a power law, suggests that the radiation populations of $e^-$ have $2 \leq p \leq 4$ - but invoking IC could narrow this range down to $2 \leq p \leq 3$. Roughly 10% of the spectra have no high-energy power law component. These spectra can be either those classified as no high energy (NHE) pulses [8] or those with $\beta \leq -4$. Such values can be interpreted as representing the Wien part of spectrum (e.g., resulting from a thermal particle distribution) or a power law spectrum that has suffered some absorption at the high end.

Here, I report on spectral evolution sequences for GRB pulses. I discuss the spectra in the comoving frame only, since the purpose is to account for spectral slopes that are sufficiently steep, so that they can result in observed spectra consistent with the fits to BATSE data (e.g., [1]).

**SYNCHROTRON SELF ABSORPTION**

As long as a *high* $\alpha$ spectrum is produced locally, all lower $\alpha$ values can be reproduced by the integrations necessary to obtain the observed spectra and can be attributed to time dilation and aberration of photons, adiabatic dilution of the $e^-$ distribution, inhomogeneous conditions in the emitting region. Here, I examine whether a steep slope spectrum ($\alpha \geq 1$) can be generated in an internal shock flow (external shocks are produced further out in the flow and thus involve less dense material). I pick typical values for the global parameters: total available luminosity per unit solid angle of $10^{52}$ erg/s/sterad ($L_{52}/\Omega = 1$), variability timescale
$t_{\text{var}} = 0.01$ s, and $\Gamma_b = 300$ (note that $\Gamma_b$ cannot be arbitrarily large even for a very clean flow because of Compton drag, [9]). Figure 1 shows the range in particle number density $n_e$ and magnetic field $B$ that would place $\nu_{\text{obs}}$ in the 30-300 keV range. This frequency is defined as the one where the optical depth to synchrotron is 1. The spectral slope below that will be 1 (or 1.5 for emission from a power law that is optically thick above the peak). The calculation is performed for a power of $e^s$ with index $p = 2.5$ (the results depend very weakly on $p$) peaking at $\gamma_{\text{min0}} = 10^3$, one peaking at $\gamma_{\text{min0}} = 10$, and a thermal distribution with $kT = 50$ keV. These constitute the simplest cases one would test. A more realistic case, where the $e^-$ spectrum results from continuous ejection with constant density and cooling via synchrotron emission only, for the first $1/10$th of the duration of the pulse, is calculated as well. To the left of the diagonal lines, the dominant cooling mechanism for the $e^-$s at peak energy is bremsstrahlung (therefore, the usual assumption of the emission being due synchrotron is no longer valid). As seen, in order to get $\nu_{\text{obs}}$ in the BATSE range, for an $e^-$ distribution peaking at $\gamma_{\text{min0}} = 10^3$ and for an equipartition magnetic field value, one would need the number density of particles to be roughly $10^3$ to $10^5$ of that of the protons in the flow. If one allows for the cooling of the $e^-$ distribution, the requirement on $n_e$ is more severe. Having a thermal particle distribution, while it relaxes the constraint on $n_e$ it requires a flow that is strongly magnetically dominated. Having a shorter variability timescale (and/or

**FIGURE 1.** Values of the magnetic field and the particle number density for which the synchrotron spectrum turns optically thick in the 30-300 keV range. On the facing axes are given the corresponding equipartition values for a flow of $t_{\text{var}} = 0.01$ s, $L_{52} = 1$, and $\Gamma_b = 300$. 

![Graph showing magnetic field and particle number density](image-url)
lower $\Gamma_b$) implies a denser environment and this results in lower equipartition fractions \( \text{e.g., for } t_{\text{var}} = 1 \text{ ms and } \Gamma_b = 200, \epsilon_B \approx 1 \) would require $\zeta = 10^3$) but also makes bremsstrahlung the dominant cooling mechanism for the $e^-$ peak. One could therefore conclude that it is not possible to have $\nu_{\text{obs}}$ in the BATSE window, if the emitting environment is that of internal shocks and the emission mechanism is synchrotron of the available $e^-$s. There is a possibility though to substantially increase the number density of emitting particles by including the $e^-e^+$ pairs that are produced in the flow due to pair opacity of the interactions of hard IC photons [4], [3]. But these pairs should be added with high densities and very hard spectra (i.e., be produced abundantly and get accelerated immediately).

**SPECTRAL EVOLUTION SEQUENCES**

I calculate spectral evolution sequences for continuous injection of particles with a prescribed power distribution (consisting of a relativistic Maxwellian at low energies, $\sim \gamma^2$, and a power law, $\sim \gamma^{-p}$ above the peak, $\gamma_{\text{min0}}$, and constant number density) and losses through adiabatic expansion, synchrotron and IC radiation in a region that is expanding at constant rate. The synchrotron and multiply (up to $\sim 10$) IC upscattered spectral components that result form the distribution at hand are calculated. The pair production is evaluated following the prescription of [10] (valid for scattering of photons with very different energies). This allows us to evaluate the attenuated hard spectrum, the pair distribution (which is a power law peaking at $\gamma \approx 1$ with index that of the hard photons). At each timestep, the number of $e^-$s with energies in the first bin are added to a population of cold $e^-$s which are used in calculating the down-scattered spectrum. At the end of each cycle the pairs are added to the $e^-$ distribution at an average constant rate (following two different prescriptions: (i) the aforementioned power law, (ii) a thermal distribution of 50 keV [3]). Details of the calculation will appear in a forthcoming paper.

Values of parameters close to equipartition and a low $\Gamma_b$ turn the spectra optically thick to pair production. In the absence of reacceleration, the pairs will contribute to absorption ($\nu_{\text{abs}}$ can reach up to a few keV), modest upscattering, and will provide abundant cold particles that down-scatter hard photons. Given a sufficient number density of cold $e^-$s in the flow, the hard photons will lose energy in successive scatterings. If the optical depth of cold $e^-$s is $\tau_{e}$, and for scatterings in the Thompson regime, a cut-off will appear at around $\Gamma_b m_e c^2 / \tau_e^2$. Requiring such a cutoff at 300 keV introduces a lower limit on the number of cold $e^-$s (and $e^+$) in the flow of $n_e \geq 6.5 \times 10^{13} / \sqrt{\Gamma_b t_{\text{var}}}$. Even if all the $e^-$s of the flow (those coming from the ionization of the explosion material) were cold they would not be able to account for the cut-off. This is possible in a situation where the flow is very optically thick to pairs. Pair production interactions of photons eliminate all photons that in the comoving frame have energies above 0.5 MeV. This creates a large number of cold pairs that subsequently down-scatter the hard photons (all scatterings take place...
in the Thompson regime). A rough estimate shows that for a cut-off at 300 keV, the product of the $e^-$ and IC radiative efficiency must be $\varepsilon_{e}\varepsilon_{ic} \approx 0.077 \eta^{9/2} \Gamma_{b}^{9/2} \frac{L_{\nu}}{\Omega}$ where the specific entropy of the flow $\eta$ and $\Gamma_{b}$ are measured in units of 100.

The $\beta$ distribution argues in favor of a particle acceleration mechanism resulting to a power law distribution in most of the pulses. A simple way (and an alternative one to the downscattering by cold $e^-$s) to explain the very steep high energy spectra (or NHE pulses, [8]) is by invoking a failed particle acceleration process. In this case, the $e^-$ distribution is either thermal, or a narrow Gaussian centered at $\gamma_{\text{min0}}$ and the power law extension is suppressed.

**CONCLUSIONS**

Observed synchrotron spectra can have any $\alpha$ value above -2/3. The $\sim 30\%$ of the spectra that require a higher value imply optically thick conditions in the BATSE window. For this, one infers high values of particle densities and a consistent spectral modeling calls for inclusion of bremsstrahlung emission. Pairs are present in the flow and they reach maximum density at around the pulse peak. They contribute to absorption, but since they are created with low energies they cannot push $\nu_{\text{abs}}$ into the BATSE window, unless they are accelerated. They may cause a changing spectral index through Comptonization (for very short pulses). They can provide a time varying population of cold particles that may be responsible for the lack of high energy emission (or steep fall off) of about 10\% of the spectra.

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