Probing the Emission Sites of GRBs

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ABSTRACT I present a computationally efficient way to account for synchrotron and its inverse Compton scattered emission along with the resulting radiative losses, in a self-consistent way, for a relativistic distribution of electrons continuously injected in an expanding region. This approach permits the exploration of the wide parameter space of the physical processes in a shock. I apply it to the picture of “internal shocks” for the description of Gamma Ray Bursts. I use the properties of the time-integrated spectra as defined mainly by observations by BATSE, EGRET, and Ginga to impose constrains on the parameter space. I discuss the corresponding shock properties and one of the ways in which INTEGRAL can provide further insight.

KEYWORDS: gamma rays: bursts —gamma rays: theory —radiation mechanisms: non-thermal

1. INTRODUCTION

A large database of Gamma Ray Bursts (GRB) has be accumulated by BATSE, over the 7.5 years of its operation. The recent detections and follow-up observations of fading and softening counterparts by the BeppoSax satellite have furnished concrete proof of both the extragalactic origin (e.g., Kulkarni et al. 1998) and relativistic expansion (Frail et al. 1998) of the sources. The BATSE database reveals a rich morphology of lightcurves as well as spectra. Most of the lightcurves are complex and highly structured pointing to an underlying “central engine”. The spectra are wide, non-thermal, and they usually exhibit one spectral break, the position and slopes away from which have considerable scatter. The spectral shapes suggest shock acceleration and non-thermal radiation processes.

Based on these properties (proven or safely inferred), I examine the time integrated spectra resulting from synchrotron ($Sy$) and inverse Compton scattering ($IC$) from $e^-$ continuously injected in a propagating shock. The cooling of the assumed injected power law is calculated self-consistently. I develop a computationally efficient scheme that is appropriate for parameter searches in the wide dynamic range of the shock properties. I use the collective spectral properties of GRBs as established by the observations of BATSE, EGRET, and Ginga, for the purpose of constraining the physical parameters of the shocks.

Fitting of BATSE time integrated spectra (Band et al. 1993) by a broken power law gives $\alpha \in [-1.5, 2]$ and $\beta \in [-2.5, -1.5]$, for the slopes, while the spectral break shows a spread between below 100 keV and above a few MeV. Moreover, spectra of COMPTEL (Hanlon et al. 1994) and EGRET (Catelli et al. 1997) bursts are fitted by a single power law of $-1.6 \lesssim \beta \lesssim -3.6$ (seemingly an extension of the BATSE high energy portion) with no indication of a high frequency cut-off. Nevertheless, searches in the 10’s of GeV to 100’s of TeV range proved fruitless (Aglietta et al. 1996).
To the soft side of the BATSE window, early experiments established an \textit{X-ray paucity}, i.e., the emission in the few keV range lies below a few percent of that in the few 100’s of keV. Recently, there has been growing evidence that this behavior is not shared by the full body of GRBs. BATSE finds an X-ray excess rather than a deficiency below 20 keV in 15% of the examined sample \cite{Preeceetal96} and so does Ginga in about 40% of its sample \cite{Strohmayeretal97}.

2. THE PHYSICAL MODEL

I consider a distribution of relativistic $e^-$ injected at a constant number density (i.e., per volume rate) in a volume that is increasing at constant speed. This could be a region in a flow that is being shocked by a sequence of similar shocks, being energized continuously at its base and growing due to the propagation of the first shock front. For the energy distribution of the $e^-$, I assume that a hard power law tail develops above $\gamma_{m,o}$. The power law index $p$ and the peak of the distribution $\gamma_{m,o}$ are free parameters. For an injection duration of $t_o$ and total number density $n_e$, the energy distribution of the rate is

$$n_\gamma \sim \frac{n_e}{t_o \gamma_{m,o}} \left\{ \begin{array}{ll}
\gamma_{m,o}^{\gamma - 1} e^{1 - \gamma/\gamma_{m,o}}, & \gamma < \gamma_{m,o} \\
\frac{\gamma}{\gamma_{m,o}}^{-p}, & \gamma_{m,o} \leq \gamma \leq \gamma_{M,o},
\end{array} \right. $$

(1)

where the hard end of the distribution $\gamma_{M,o}$ is determined at every timestep by the size of the emitting region. All quantities are in the frame co-moving with the flow.

The distribution cools under $Sy$ and the $IC$ scattering of it. Fitting the resulting time integrated spectrum, one may express all its characteristic frequencies in terms of the corresponding energies of the $e^-$ distribution, the magnetic field $B$, and $p$. Therefore, given the shape of the $e^-$ distribution at every instant that follows from the injection prescription and cooling in the global magnetic and radiation fields, one can describe parametrically the $Sy$ component of the spectrum. The same can be done with the $IC$ component, assuming the spectral shape results from scattering of monoenergetic radiation with the mean frequency of $Sy$.

For the description of the time integrated spectra, the characteristic energies of the $e^-$ distribution are sufficient. In order to avoid the expensive computation of the evolution of the $e^-$ distribution at every timestep, with self-consistent account of the $IC$ emission, along with the spectral distribution of the emission, the following procedure is adopted: At every timestep, the evolution of the edges $\gamma_m$ and $\gamma_M$ of the $e^-$ distribution is calculated given the total number density of $e^-$ present in the region and the radiation energy density and mean frequency of the synchrotron radiation produced at all previous timesteps. Cooling is evaluated in two limiting cases, accounting for $IC$ scattering in the Thomson and the extreme Klein-Nishina (KN) regime, with an adaptive timestep to insure smooth transition. The power law develops a knee which, at the end of the injection (assumed to last as long as the emission), is at $max\{\gamma_{m,o}, \gamma_{M,t_o}\}$. Apart from $\langle \gamma^2 \rangle_t$, the value $\gamma_{KN}$ is computed were the distribution may flatten (this happens if losses in the extreme KN regime
outweigh those of $S_y$). From the evolution of the edges of the $e^-$ distribution, the total power emitted is also obtained; the relative strength of the $S_y$ and IC components is weighted by the cooling timescales of $\gamma_{m,o}$.

Tying the described physical system to the proposed picture of internal shocks for GRB (Mészáros & Rees 1994), I express the needed quantities in terms of the physical properties of the source, with appropriate parameterization. Internal shocks develop when a flow with an intrinsic variability on $t_{\text{var}}$ dissipates its fluctuations. The flow is further characterized by a total energy $E_o$, solid angle $\Delta\Omega$, mass injection rate $\dot{M}_o$, and duration of the activity $t_w$ (which also determine the flow’s bulk Lorenz factor $\Gamma \lesssim \eta \simeq E_o/\dot{M}_o t_w c^2$). Such internal shocks develop at $r_d \simeq \Gamma^2 ct_{\text{var}}$ from the center of the activity. These determine the energy and mass densities at the dissipation site to which the properties that are relevant to the emission processes are linked. Consequently, the magnetic field energy density is expressed as a fraction $\lambda$ of the internal energy, the number density of the injected $e^-$ as a fraction $\zeta$ of the $p$ energy (assuming equal numbers of $p$ and $e^-$ in the flow), and the mean energy of the injected $e^-$ distribution by $\kappa$. The efficiency of passing energy from the main inertia carriers to $e^-$ during acceleration, is $\varepsilon_{pe} = \zeta \kappa m_e/m_p$ with $\kappa \leq \zeta m_p/m_e$. Also, in this picture, $t_o = \Gamma t_{\text{var}}$.

3. PARAMETER SEARCH

A large fraction of the time-integrated spectra shows a break in the BATSE window. Furthermore, the self absorption frequency is scarcely met in this range. Fixing the $e^-$ spectral index to $p = 3$, close to the full range of fitted spectral slopes is obtained, depending on the characteristic $e^-$ energy that falls in the BATSE window. The criteria that I adopt to search for parameters that satisfy the constraints are set mainly by the data collected by BATSE, EGRET and Ginga—and will be referred to as BEG. These are: 1) The burst is “detectable” by BATSE, i.e., $\nu F_\nu \gtrsim 10^{-8}\text{erg/cm}^2$. 2) Losses in the KN regime should not affect the shape of the $e^-$ distribution in the range probed by BATSE. 3) One of the spectral breaks of either the $S_y$ or the IC component that correspond to $\gamma_{m,t_o}$, $\gamma_{m,o}$, or $\gamma_{\text{knee}}$, or, the frequency below which the $S_y$ turns over to the Rayleigh-Jeans slope, or its IC upscattered counterpart falls in the BATSE window. 4) The photon number index in the EGRET range, up to 300 MeV is $\beta_{300\text{GeV}} \lesssim -1.6$. 5) The burst is X-ray deficient: $(\nu F_\nu)_{\text{2keV}} \leq 5\% (\nu F_\nu)_{300\text{keV}}$. 6) The burst is X-ray rich: $5\%(\nu F_\nu)_{300\text{keV}} \leq (\nu F_\nu)_{2\text{keV}} \leq 2(\nu F_\nu)_{300\text{keV}}$.

I adopt $E_o = 10^{51}$ erg, $\Delta\Omega = 0.12$ rad and $100 \leq \Gamma \leq 300$, in accordance with estimates implied by afterglow observations. Searches in the shock parameter space (i.e., $\kappa$, $\lambda$, and $\zeta$) are conducted with the following combinations of the BEG criteria: 1; 1, 2, and 3; 1, 2, 3, and 4; 1, 2, 3, and 5; 1, 2, 3, and 6.

4. RESULTS AND DISCUSSION

Even the most restrictive of the parameter regions allow for a wide range of
spectral shapes. Only for the highest possible magnetic field values does the Sy component lie in the BATSE window and, in most of these cases, copious photon production results in a prominent component (pair absorbed, in cases) in the EGRET window. This is inconsistent with observations. Upon closer inspection of the resulting spectra, many parameters can be further excluded based on the broader spectra features. Requiring the thermal slope to be way below the BATSE window leaves very little allowed parameter space indeed. Hence, I tentatively conclude that the transition to the optically thick part of the spectrum happens at a frequency fairly close to the low edge of BATSE. This is in agreement with the suggestion of the Ginga spectra analysis of a second spectral break around 5 keV (Strohmayer et al. 1997).

The present analysis suggests that IC is most often the BATSE component. A rather narrow range of the $e^-$ distribution parameters corresponding to a low efficiency for transferring of energy from $p$ to $e^-$ ($0.1\% \lesssim \epsilon_{pe} \lesssim 1\%$), combined with a wide range in the fraction of the magnetic field energy density ($10^{-8} \lesssim \lambda \lesssim 10^{-2}$) can reproduce the full range of the documented properties. With IC being in the BATSE range, higher $B$ field values lead to a more pronounced and narrowly spaced Sy component thus resulting in an X-ray excess case, while weaker field suppresses Sy emission exposing the steep (thermal slope) part of the IC component therefore listing the case as an X-ray deficient one.

Although this is not a comprehensive parameter search, these observations should hold roughly unchanged in general too. There is no strong dependence of the allowed parameter space on $t_{\text{var}}$, $\Gamma$ is tightly constrained in a narrow range around 300, and the shock properties should not depend on the central engine operation lifetime or total energy (apart from affecting detectability).

One of the suggestions of this analysis is that the transition to the optically thick portion of the time integrated spectra, happens close to the low end of the BATSE window (some times inside it). Extending the simultaneous spectral coverage down to the keV range (which is in the INTEGRAL capabilities) will help answer this question thus providing valuable insight into the conditions of the associated shocks.

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