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A Photohadronic Instability Model for GRB Prompt Emission

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Abstract: The mechanisms behind gamma-ray bursts (GRBs) are not yet well understood. Here we investigate a model where a spectral energy distribution (SED) that looks surprisingly like a typical GRB prompt emission is generated starting with merely high energy protons and a magnetic field. Using a self-consistent, time-dependent code we show that when the density of such protons exceeds a certain threshold their energy is converted explosively to lower energy photons through a series of positive feedback loops. At even higher densities, Compton scattering of cold electrons shapes the low energy part of the SED into the familiar Band function, a distinctive peak between 1-10 keV (in the comoving frame) in GRB observations. This approach, although similar to the photospheric GRB model, also allows us to investigate the neutrino emission, which can be compared with recent IceCube limits.

1 Introduction / The model

Several models have been proposed to explain the prompt emission of Gamma-ray bursts (GRBs), starting with the common assumption that internal energy is been released through an ultrarelativistic outflow. In synchrotron models an electron population is assumed to be accelerated into a power law distribution at a large distance from the base of the jet (see [4] for a review). In photospheric models (e.g. [5, 3]) electron-positron pairs radiate when the jet becomes sufficiently transparent. Here we take a different approach: starting with a power law distribution of protons we will show how a spectrum similar to that of GRB prompt emission arises through comptonization of the radiation and cooled pairs that result from a set of interconnected interactions.

Let us assume that protons are being accelerated within a conical jet flow. The essential variables can be reduced to the kinetic luminosity, $L_{\rm k}$, the ratio of Poynting to kinetic luminosity, $\epsilon_{\rm B}$, the bulk Lorentz factor of the flow, Γ, and the variability timescale of the source, δt. From them we can derive all other parameters.

The injected protons will produce synchrotron radiation and then interact with it through photohadronic interactions as has been shown in [2]. For high enough proton compactnesses, the compactness of the proton synchrotron component may exceed the critical value for the onset of the instability called “automatic photon quenching” - the system then becomes supercritical [6]. The critical proton compactness for supercriticality is found to be: $\ell_{\rm p}^{\rm inj} \ge 5 \cdot 10^{-4} \frac{\Gamma_2^2}{\epsilon_{B,-1}^{1/2} L_{k,52}^{1/2}} = \ell_{\rm p,crit}$.

In such a case, as the system goes increasingly deep into the supercritical regime the peak of the photon spectrum will shift to lower energies but higher fluxes, since more photons are produced but they lose their energy with increasing efficiency through Compton interactions with cooled electrons. The result may closely resemble a GRB Band function, both in shape and in energetics.

2 Numerical Results

In each test run, a proton distribution with slope $p = 1.5$ was continuously injected and the system was allowed to reach steady state. If the system achieved supercriticality, we could then assess the

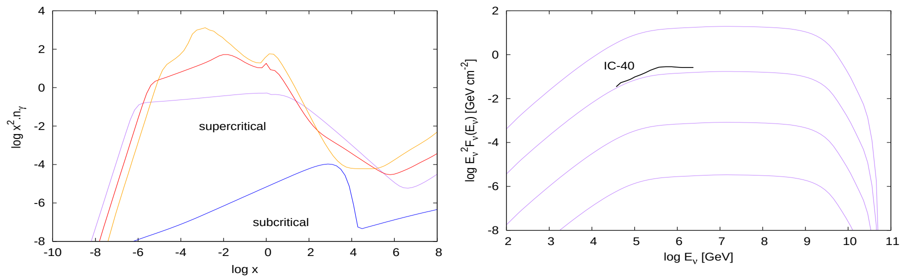

Figure 1: Left: Steady-state spectra of photons resulting from a power-law proton injection $\delta t = 0.01$s, $L = 10^{52}$, $\epsilon = 0.1$ and $\Gamma = 10^{2.75} - 10^{2}$, with increments of 0.25 in logarithm (top to bottom). Right: Neutrino fluences resulting from a power-law proton injection $\delta t = 0.1$s, $L = 10^{53.5}$, $\epsilon = 0.1$ and $\Gamma = 10^{2.25}$, for events at distances $z = 0.01$, $z = 0.1$, $z = 1$ and $z = 10$ (top to bottom). Also shown is the IceCube-40 array limit from [1].

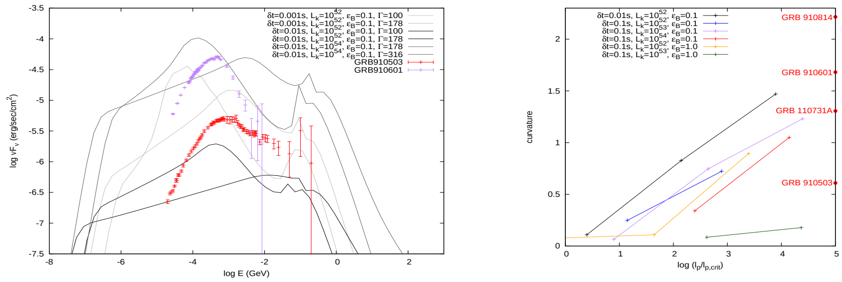

Figure 2: Left: A collection of steady-state spectra of photons resulting from various free parameters (see legend), taken at the same distance as GRB 910503 and GRB 910601, shown for comparison. Right: Spectral curvature as a function of injected proton luminosity, for six different sets of the remaining free parameters. The observed spectral curvatures of some GRBs are shown as a reference; they do not correspond to any known values of $\ell_{\rm p}^{\rm inj}$.

curvature of the comptonized component. In the left panel of Fig.1 we show the progression of photon spectra for a set of parameters with decreasing Γ. As can be seen in the right panel of Fig.1, neutrino fluences vary depending on source distance but even for nearby events they struggle to surpass the IceCube-40 sensitivity limit.

The left panel of Fig.2 displays a small sample of spectra with different initial parameters, ascribed to a source at a distance of $z = 0.4$ and compared with the spectra of two known GRBs at that distance. No attempt was made at an actual fit, but the figure demonstrates how our free parameters can accommodate a wide range of Band functions. As the right panel of Fig.2 shows, the curvature is generally dependent on how far the protons start out within the supercritical regime, but is also modulated by the other parameters. Further study will explore the scope and limitations of this model.

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