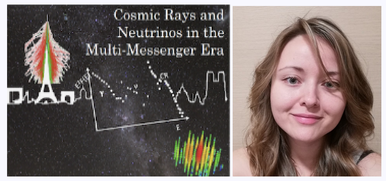

A Marginally Fast-Cooling Proton-Synchrotron Model for Prompt GRB Emission

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Introduction

A small fraction of GRBs with available data down to soft X-rays (~ 0.5 keV) have been shown to feature a spectral break in the low energy part of their prompt emission spectrum [1]. The overall spectral shape is consistent with optically thin synchrotron emission from a population of marginally fast cooling particles [2]. In this work [3] we consider the hadronic scenario and investigate the idea that the prompt emission of these GRBs originates from *relativistic protons that radiate synchrotron in the marginally fast cooling regime*. This is defined as the regime where protons of minimum energy cool on a timescale shorter or comparable to the dynamical timescale of the source. We compute the source parameters required for such a scenario and investigate how additional processes, namely photohadronic interactions and gamma-gamma pair production, contribute to the overall spectrum. We numerically compute the observed photon spectra and calculate the expected high-energy neutrino emission following the assumptions of this work.

Model Parameters

We assume that at a distance R_γ from the central engine of the GRB, relativistic protons are injected inside a spherical region that moves with a bulk Lorentz factor Γ. This spherical region has a comoving radius $r_b = R_\gamma/\Gamma$ and contains a tangled magnetic field of comoving strength B. Relativistic protons produce synchrotron photons that also serve as targets for photopion production. We use the best-fit values for 4 observables from [1], namely $E_{pk,obs}$, $F_{c,obs}$, γ_m/γ_c and $t_{\gamma,obs}$, to compute the source parameters in the proton synchrotron model.

$$B = \frac{1}{\Gamma^{1/3}}\left(\frac{27\pi q\hbar m_e c(1+z)}{\sigma_T^2 t_{\gamma,obs}^2 E_{c,obs}}\right)^{1/3}\left(\frac{m_p}{m_e}\right)^{5/3}, \quad r_b = 2ct_{\gamma,obs}\Gamma(1+z)^{-1} \tag{1}$$

$$\gamma_m = \sqrt{\left(\frac{\gamma_m}{\gamma_c}\right)^2 E_{c,obs}\frac{4\pi m_e c(1+z)}{3q\hbar}\frac{m_p}{m_e}\frac{1}{B\Gamma}}, \qquad L_p \approx \frac{3L_{iso}}{\Gamma^4} \tag{2}$$

where $L_{iso} = 4\pi d_L^2 F_\gamma$ is the bolometric γ-ray luminosity of the prompt emission in the observer's frame, and the bolometric flux, F_γ.

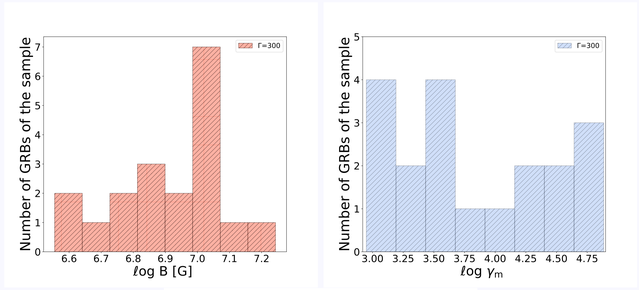


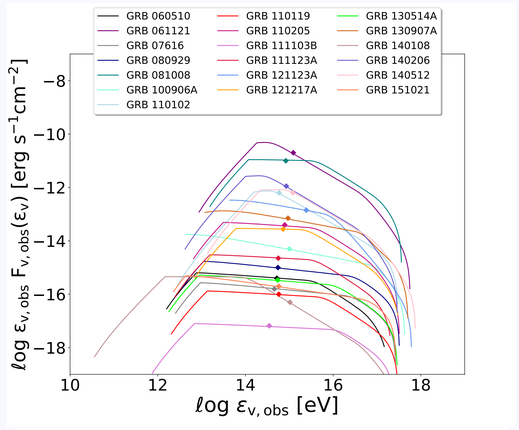
Figure 1: Logarithmic histograms of parameter values for a sample of 19 GRBs [1]. Results for another choice of Γ can be found using the scaling relations $B \propto \Gamma^{-1/3}$, $\gamma_m \propto \Gamma^{-1/3}$, $L_p \propto \Gamma^{-4}$.

Photohadronic processes & neutrino spectra

We calculate semi-analytically the photopion production efficiency and the all-flavor neutrino flux for the parameter values of Fig 1.

$$\varepsilon_{\nu,obs}F_\nu(\varepsilon_{\nu,obs}) \approx \frac{3}{8}\Gamma^4 f_{p\pi}(\varepsilon_p)\frac{\varepsilon_p L_p(\varepsilon_p)}{4\pi d_L^2} \tag{3}$$

where $f_{p\pi}$ is the photopion production efficiency of protons with comoving energy ε_p and d_L is the GRB luminosity distance. Our results are presented in Fig. 2.



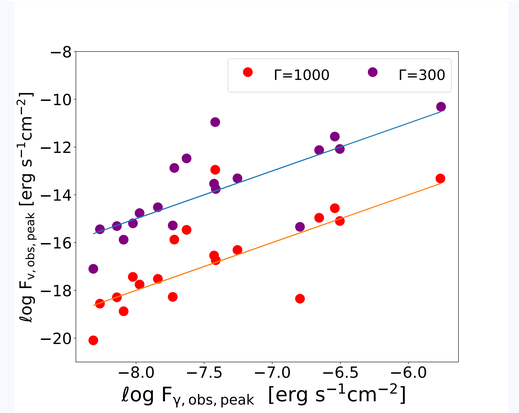


Figure 2: *Top:* Predicted all-flavor neutrino energy flux spectra for GRBs from the sample of [1] assuming $\Gamma = 300$. *Bottom:* Scatter plot of the peak all-flavour neutrino energy flux as a function of the peak γ-ray energy flux for $\Gamma = 300$ and 1000.

Numerical Results

We investigate next the role of physical processes that are not included in our semi-analytical calculations (e.g., photon-photon pair production, pion and muon cooling). For this purpose, we utilise a time-dependent numerical code [4] that follows the evolution of spatially averaged particle populations inside a homogeneous spherical emitting region, while taking into account all relevant physical processes.

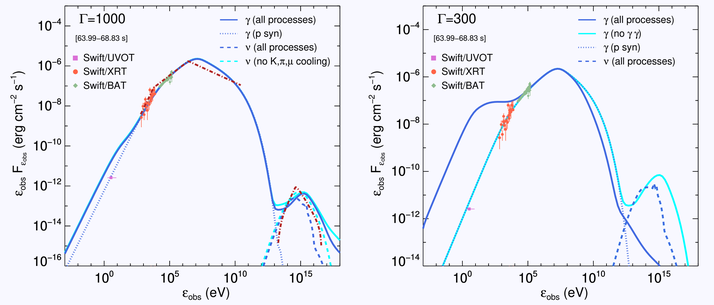


Figure 3: Predicted photon (solid blue line) and all-flavor neutrino (dashed blue line) energy spectra of GRB 061121 in the proton-synchrotron prompt emission model for $\Gamma = 1000$ (left panel) and $\Gamma = 300$ (right panel).

Γ	B (G)	r_b (cm)	γ_m	L_p (erg s^{-1})
300	4.9×10^6	3.8×10^{12}	3.2×10^4	4.1×10^{42}
1000	3.7×10^6	1.3×10^{13}	2.1×10^4	3.4×10^{40}

Table 1: Parameter values used in the numerical proton synchrotron model. We choose $p = 2.6$ and $\gamma_{max} = 10^6$ for both cases

Conclusion

- The low energy part of the spectrum is not in good agreement with the observations when photomeson production and photon-photon pair production processes are taken into account for $\Gamma < 1000$.
- The predicted diffuse neutrino flux is $2 \sim 3$ orders of magnitude lower than the one of standard neutrino production models.
- The proton synchrotron scenario for GRB prompt emission demands very strong magnetic fields, resulting in very high magnetic jet powers.

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