Gamma-ray burst models with general dynamics and fits to Fermi LAT bursts

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We present a dissipative photospheric model for gamma-ray bursts where the usual Band peak around MeV energies arises as synchrotron emission from around the photosphere. We treat the initial acceleration in a general way and the GeV emission arises as the interaction of photospheric radiation and the shocked electrons at the deceleration radius. We show some applications of this model.

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1 Introduction

Observations of GRBs at GeV energies by Fermi LAT have uncovered new properties which warrant an explanation. To explain the GeV emission of gamma-ray bursts observed by LAT, we worked out the details of a dissipative photospheric scenario in a magnetically dominated jet and its interaction with the shocked circumstellar material \[3\]. In this scenario, the MeV peak is given by synchrotron radiation from close to the photosphere, the GeV emission is given by the interaction of the photospheric photons with the shocked electrons at the deceleration radius. In the magnetically dominated case the dynamics in the acceleration phase is defined by $\Gamma(r) \propto r^{1/3}$ \[2\]. We have worked out the details of a more general model, allowing for the $\Gamma(r) \propto r^\mu$ type of acceleration which encompasses both the magnetic and the baryonic model at the two extremes \[5\]. We have shown through detailed fitting that the model can adequately reproduce the Fermi GBM and LAT observations. In \[4\], we have proven that GRB 110721A, with an unusually high peak energy \[1\], can be explained in terms of a dissipative photosphere model, where the dynamics is baryonic or intermediate between magnetic and baryonic.

2 Dynamics

The jet can accelerate more slowly than in the usual baryonic model (e.g. due to magnetic dissipation):

$$\Gamma(r) \propto \begin{cases} r^\mu & \text{if } r < r_{\text{sat}} \\ \text{const.} & \text{if } r_{\text{sat}} < r \end{cases}$$

We can define a critical Lorentz factor (from $r_{\text{sat}} = r_{\text{phot}}$), probing whether the photosphere is in the acceleration or coasting phase of the dynamics:

$$\eta_T = \left( \frac{L \sigma_T}{8 \pi m_p c^3 r_0} \right)^{1/3 + 3\mu} \approx \begin{cases} 120 \ L_{53}^{1/6} r_{0.7}^{-1/6} & \text{if } \mu = 1/3 \\ 1300 \ L_{53}^{1/4} r_{0.7}^{-1/4} & \text{if } \mu = 1 \end{cases}$$

If $\eta > \eta_T$, the photosphere will be in the acceleration phase, typical for magnetically dominated outflows, $\mu \approx 1/3$. In case of $\eta < \eta_T$, the photosphere will occur in the acceleration phase, typical for baryon dominated outflows, $\mu \approx 1$ (see Fig. 1).

The physical parameters with some representative values are $L \approx 10^{53}$ erg/s luminosity, $\eta \approx 600$ coasting Lorentz factor, $r_0 \approx 10^7$ cm launching radius, $\Gamma_r \approx 1$ shock Lorentz factor. According to the model, the peak energy dependence is:

$$\varepsilon_{\text{peak}} \propto \begin{cases} \frac{3\mu+1}{4\mu+2} L^{3/2} \eta^{3\mu/4+1} r_0^{\mu/3} \Gamma_r^3/(1+z) & \text{if } \eta > \eta_T \\ L^{-1/2} \eta^3 \Gamma_r^3/(1+z) & \text{if } \eta < \eta_T \end{cases}$$

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Figure 1: Schematic view of the Lorentz factor evolution with radius in the magnetically dominated (\(\mu = 1/3\), top diagram) and in the baryon dominated (\(\mu = 1\), bottom diagram).

A subdominant thermal component is also present:

\[
T_{\text{obs}} \propto \begin{cases} 
L^{\frac{14\mu}{(2\mu+1)}} \eta^{\frac{2-2\mu}{\eta(2\mu+1)}} r_0^{\frac{10\mu-1}{\eta(2\mu+1)}} / (1 + z) & \text{if } \eta > \eta_T \\
L^{-\frac{5}{12}} \eta^{\frac{8}{3}} r_0^{1/6} / (1 + z) & \text{if } \eta < \eta_T.
\end{cases}
\]

3 Discussion

3.1 Detailed modeling of the magnetic case (\(\mu = 1/3\))

The jet is accelerated by magnetic fields until saturation (\(R_{\text{sat}}\)). Typically the photosphere occurs above the saturation radius. Semirelativistic shocks at the photosphere, emit synchrotron radiation and give rise to the Band peak. External inverse Compton upscattering of the prompt photons on the shocked electrons at the deceleration radius give the GeV emission. Most of the interaction will occur at \(\sim 1/\Gamma\) angle between the photon and energy momenta.

3.2 Fitting

We have developed a model for a general \(\mu\) (see eq. 3) and used it to fit four bright Fermi LAT detected GRBs: 080916C, 090510A, 090902B, 090926A. We use the
Figure 2: Time integrated model spectrum showing various components. At high energies the components give a simple power law. Upper and lower thick gray curves represents the spectrum with and without reverse shock.

response matrices of GBM and LAT to convolve the theoretical spectra and get the count spectrum. We adjust the parameters of the model to get the best fit. We show our model with its components on figure 3 as an example for the fit of the baryonic model for GRB 090510A.

3.3 GRB 110721A

This burst has an extremely high peak energy ($\approx 15$ MeV) at the onset. It is hard to reconcile this with the standard internal shock scenario, but can be accounted for by a dissipative photosphere model with general dynamics [4]. Namely, the $\mu = 1$ and $\mu = 0.5$ cases allow for the high observed peak energy for reasonable parameters, while $\mu = 1/3$ is hard to reconcile with the observations from this burst.

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