

Multi-GeV lightcurves: possible hints for the emission mechanism

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Although the Fermi observatory has reported delayed onsets of GeV emissions, the photon statistics are not sufficient to distinguish the emission mechanisms. Future multi-GeV observations such as CTA may give us precise lightcurves that can be compared with lower energy bands. In this paper we show our time-dependent simulations for leptonic and hadronic models. Our results suggest that the multi-GeV lightcurves are powerful tool to probe the GeV emission mechanisms.

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1. Introduction

The Large Area Telescope (LAT) on board the *Fermi* Gamma-Ray Space Telescope revealed that some fraction of GRBs show delayed onset of GeV emission as seen in GRB 080916C [1]. Furthermore, GRB 090510 [2], GRB 090902B [3], and GRB 090926A [4] have an extra spectral component that dominates GeV energy range. While such behaviours in GeV emissions can constrain the emission mechanisms, the photon statistics in Fermi telescope are still insufficient to confirm the correlation between GeV and MeV lightcurves quantitatively. The typical photon counts in the *Fermi*-LAT observations is a few per pulse. We may need hundreds of GeV photons or more to compare the widths of pulses with MeV pulses. In order to obtain enough photons above GeV, a much larger effective area is required. Therefore, air Cherenkov telescopes (ACT) such as Cherenkov Telescope Array (CTA) etc. can be powerful tools, if the low-energy threshold is lowered as low as 10–30 GeV. If an ACT fortunately detect a GRB similar to the *Fermi*-LAT GRBs, the expected gamma-ray lightcurve may be so precise that we can compare its variability with that for lower energy bands. This must determine the origin of GeV emissions; external or internal.

If we confirm that the GeV sources are common to the MeV emission region, the delayed onset of GeV emission will be focused on as an enigmatic signature again. This can be a hint to unravel the emission mechanism. In this paper, we consider methods to distinguish several models that explain the delayed onset, from multi-GeV lightcurves observed with ACTs.

2. SSC model

The simple synchrotron self-Compton (SSC) model can naturally explain the extra components. In this model, the delayed onset can be interpreted as a lag-time before the seed photons for SSC build up. We, Asano & Mészáros (2011) [5] (hereafter AM11) developed a time-dependent code to simulate emissions from a relativistically expanding shell. While our code is based on one-zone approximation, it can follow the injection and cooling for electrons/positrons, and production, absorption and escape for photons. The physical processes we considered are (1) synchrotron (2) Thomson or inverse Compton (IC) scattering (including the Klein–Nishina regime) (3) synchrotron self-absorption (SSA) (4) $\gamma\gamma$ pair production (5) adiabatic cooling.

For moderate magnetic fields such as $\epsilon_B/\epsilon_e = 0.1-1$, it is hard to find a delayed onset comparable to the variability timescale $R/\Gamma^2/c$. Only if we adopt a very low magnetic field (due to small ϵ_B such as $\epsilon_B/\epsilon_e \sim 10^{-3}$ and/or large radius R even for large ϵ_B), the delayed onset is reproduced by the slow growth of the seed photon field. In this case, the low magnetic field requires a large $\gamma_{e,\min}$ ($> 10^4$) to make the spectral peak energy \sim MeV, which implies that the Klein–Nishina effect is effective. This is a primary reason why the IC component grows slowly.

Only in this extreme parameter set, the one-zone leptonic model can reproduce a significant delayed onset. Even in this case, the width of the lightcurves for MeV and GeV is almost the same.

3. EIC model

Two-zone external inverse Compton (EIC) model was proposed by Toma et al. [6, 7] to explain the delayed onset of GeV emission. The MeV photons are emitted from a smaller radius, and

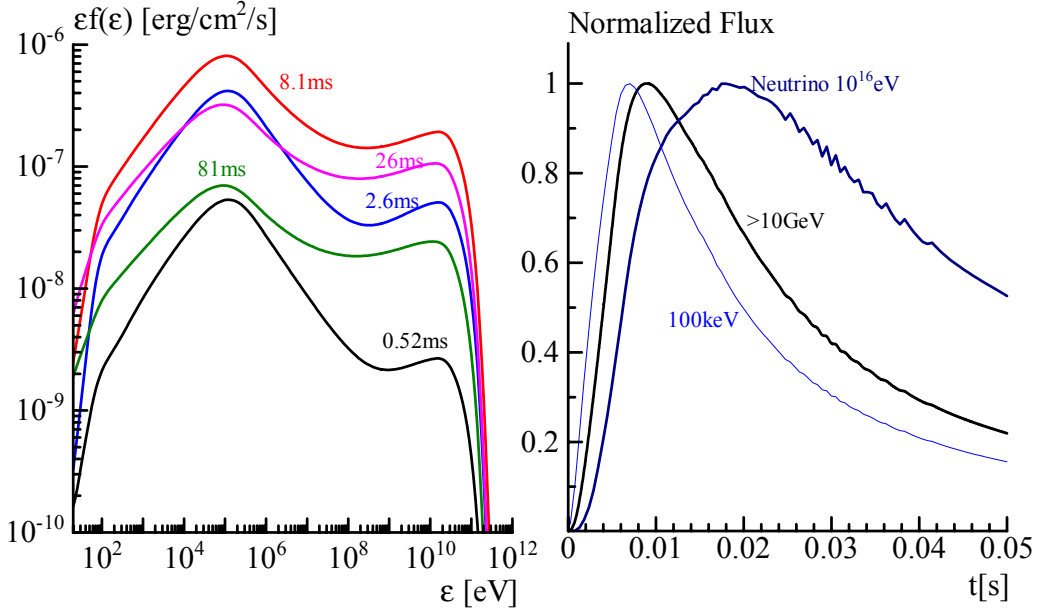


Figure 1: Spectral evolution (left) and lightcurves (right) for an observer ($z = 1$) in the hadronic model. The model parameters are $\Gamma = 800$, $R_0 = 10^{14}$ cm, isotropic-equivalent energy of electrons $E_{e,pls} = 5.0 \times 10^{50}$ erg, protons $E_{p,pls} = 6.1 \times 10^{51}$ erg, and the initial magnetic field $B'_0 = 1.9 \times 10^4$ G.

they are upscattered by accelerated electrons in an outer region. In this model, we require two different origins for the MeV and GeV components. A GeV delay larger than the typical pulse timescale appears naturally. In the frame of the outer dissipation region, the photon field coming from an inner region is highly beamed. As a result, the intensity of the scattered photons becomes anisotropic. In this case, the emission from off-axis regions ($\theta \gtrsim 1/\Gamma$) is not negligible. We also tested this case with our numerical code in AM11, and showed that the GeV lightcurve has a long tail, which is a characteristic feature of this model.

4. Opacity evolution

Using the same code in AM11, we also test the $\gamma\gamma$ -opacity evolution effect [8]. At least in our one-zone formulation, an electron injection timescale longer than the expansion timescale is required in order to observe the opacity damping. As the opacity decreases with radius R , the cut-off energy increases. So in this model, the high-energy emissions tend to delay. However, the spectral shape at the cut-off energy is not so sharp even in one-zone approximation. The spectrum can be approximated by a broken power-law, which comes from the balance between photon production and absorption in the source. Thus, the model lightcurve shows gradual GeV onset, which seems different from the observed “sudden” onset. Thus, we conclude that the $\gamma\gamma$ -opacity evolution is hard to explain the delay.

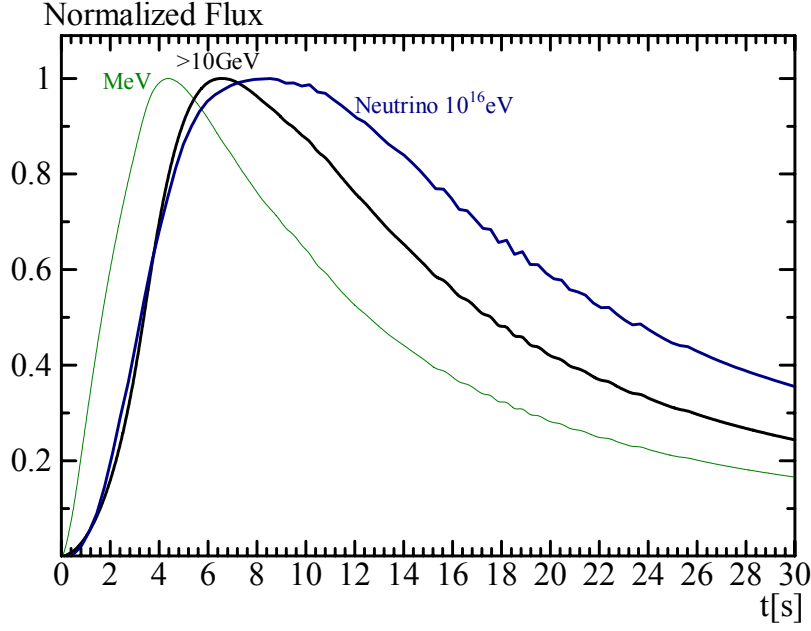


Figure 2: Lightcurves for an observer ($z = 4.35$) in the hadronic model. The model parameters are $\Gamma = 600$, $R_0 = 1.3 \times 10^{16}$ cm, $E_{e,pls} = 2.0 \times 10^{54}$ erg, $E_{p,pls} = 4.8 \times 10^{55}$ erg, and $B'_0 = 830$ G.

5. Hadronic model

We installed hadronic processes into the code in AM11, and demonstrate the lightcurves for hadronic models [8]. Hadronic models can explain the extra spectral components by the synchrotron/IC emissions from electron–positron pairs produced via the electro–magnetic cascade triggered by photopion production (hadronic cascade) [9, 10]. The maximum energy of protons gradually increases during particle injection in the shocked shell. On the other hand, the injected electrons produce a soft photon field around MeV. The spectrum of the MeV component is as soft as $\alpha \sim -1.5$, where α is the low-energy photon index. Therefore, the efficiency of photopion production grows with the proton energy. Therefore, until the maximum energy grows enough, the electro–magnetic cascade triggered by the photomeson production does not start. This yields the delayed onset of 10 GeV emissions relative to the MeV photon emission. Moreover, even after the particle injection is stopped, the residual photons in the source continuously interact with protons. As a result, the gamma-ray emissions due to the hadronic cascade last longer than the MeV emissions. An examples of the spectral evolution and lightcurves is shown in Figure 1. The characteristic feature is that the 10 GeV-lightcurve has a wider shape than the MeV-lightcurve.

As shown in Figure 1, the neutrino lightcurve shows more distinctive delay than 10 GeV-delay. This is because the GeV photons are produced from not only hadronic processes but also IC emission from primary electrons.

If we adopt a large radius, even for a large ϵ_B , the magnetic field becomes so low that the Klein-Nishina effect becomes crucial. In this case, the IC emission is negligible in GeV band. As shown in Figure 2, the delays for GeV and neutrinos are comparable.

6. Conclusion

The GeV delays can be explained either by a one-zone leptonic model with very low magnetic field, or by normal parameter range one-zone hadronic models; or also by a two-zone EIC leptonic model. However, the lightcurve behavior of these models differ substantially from each other. While the FWHMs of the MeV and GeV lightcurves are almost the same in one-zone leptonic models, the FWHM of the 1–30 GeV lightcurves in hadronic models are significantly wider than those of the 0.1–1 MeV lightcurves.

Here, we have assumed a simple Bohm-limit acceleration for electrons and protons. Of course, the lightcurve may depend on the model details of particle acceleration. The electron acceleration timescale is usually considered to be short enough compared to the dynamical timescale. However, the continuous acceleration like the second-order Fermi acceleration [11] or continuous heating [12] for electrons are recently focused on to resolve the contradictions in the low-energy spectral index etc. In such models, the lightcurve behaviour can be different from the examples shown here even in leptonic models. Another possible mechanism to delay GeV emission is the temporal evolution of the magnetic field [11]. The magnetic field amplified by some plasma instabilities can decay suddenly after a certain timescale provided by the plasma frequency. Then, IC emission becomes dominant instead of synchrotron emission. The predicted differences in the lightcurves for various models including the above models can be tested with future atmospheric Cherenkov telescopes such as CTA.

References

- [1] Abdo, A. A. et al., *Fermi Observations of High-Energy Gamma-Ray Emission from GRB 080916C*, *Science* **323** (2009) 1688
- [2] Ackermann, M. et al., *Fermi Observations of GRB 090510: a Short-Hard Gamma-Ray Burst with an Additional, Hard Power-Law Component from 10 keV to GeV Energies*, *ApJ* **716** (2010) 1178
- [3] Abdo, A. A. et al., *Fermi Observations of GRB 090902B: A Distinct Spectral Component in the Prompt and Delayed Emission*, *ApJ* **706** (2009) L138
- [4] Ackermann, M. et al., *Detection of a Spectral Break in the Extra Hard Component of GRB 090926A*, *ApJ* **729** (2011) 114
- [5] Asano, K. & Mészáros, P., *Spectral-Temporal Simulations of Internal Dissipation Models of Gamma-Ray Bursts*, *ApJ* **739** (2011) 103
- [6] Toma, K., Wu, X.-F. & Mészáros, P., *An Up-Scattered Cocoon Emission Model of Gamma-Ray Burst High-Energy Lags* *ApJ* **707** (2009) 1404
- [7] Toma, K., Wu, X.-F. & Mészáros, P., *Photosphere-internal shock model of gamma-ray bursts: case studies of Fermi/LAT bursts*, *MNRAS* **415** (2011) 1663
- [8] Asano, K. & Mészáros, P., *Spectral-Temporal Simulations of Internal Dissipation Models of Gamma-Ray Bursts*, *submitted to ApJ* (2012) [arXiv:1206.0347]
- [9] Asano, K., Guiriec, S., & Mészáros, P., *Hadronic Models for the Extra Spectral Component in the Short GRB 090510*, *ApJ* **705** (2009) L191

- [10] Asano, K., Inoue, S., & Mészáros, P., *Prompt X-ray and Optical Excess Emission due to Hadronic Cascades in Gamma-Ray Bursts*, *ApJ* **725** (2010) L121
- [11] Asano, K., & Terasawa, T., *Slow Heating Model of Gamma-Ray Burst: Photon Spectrum and Delayed Emission*, *ApJ* **705** (2009) 1714
- [12] Beloborodov, A. M., *Collisional mechanism for gamma-ray burst mission*, *MNRAS* **407** (2010) 1033