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GRB LORENTZ FACTOR CONSTRAINTS IN THE FERMI-LAT ERA

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Abstract. Recent detections of GeV photons in a few GRBs by Fermi-LAT have led to strong constraints on the bulk Lorentz factor in GRB outflows. To avoid a large $\gamma\gamma$ optical depth, minimum values of the Lorentz factor have been estimated to be as high as 800-1200 in some bursts. Here we present a detailed calculation of the $\gamma\gamma$ optical depth taking into account both the geometry and the dynamics of the jet. In the framework of the internal shock model, we compute light curves in different energy bands and the corresponding spectrum and we show how the limits on the Lorentz factor can be significantly lowered compared to previous estimates.

Our detailed model of the propagation of high energy photons in GRB outflows is also appropriate to study many other consequences of $\gamma\gamma$ annihilation in GRBs: (i) the $\gamma\gamma$ cutoff transition in a time-integrated spectrum is expected to be closer to a power-law steepening of the spectrum than to a sharp exponential decay; (ii) the temporal evolution of the $\gamma\gamma$ opacity during a burst favors a delay between the MeV and GeV light curves; (iii) for complex GRBs, the $\gamma\gamma$ opacity suppress the shortest time-scale features in high energy light curves (above 100 MeV). Finally we also consider GRB scenarii where MeV and GeV photons are not produced at the same location, showing that the $\gamma\gamma$ opacity could be further lowered, reducing even more the constraint on the minimum Lorentz factor.

Keywords: gamma-ray bursts, GRB 080916C, radiative transfer, non thermal radiation mechanisms

1 Introduction

The compactness problem. The short time scales observed in GRBs (down to a few ms) can be used to deduce an upper limit on the size of the emitting region producing γ-rays. This information combined with the huge isotropic γ-ray luminosities deduced from the measured redshifts imply huge photon densities. Then the simplest assumption of an emission produced by a plasma radiating isotropically with no macroscopic motion predicts that γ-ray photons should not escape due to $\gamma\gamma$ annihilation $\gamma\gamma \rightarrow e^+e^-$. This is in contradiction with the observed GRB spectra which are non-thermal and extend well above the rest-mass electron energy $m_e c^2 \approx 511$ keV. Observation and theory can be reconciled by assuming that the emitting material is moving at ultra-relativistic velocities (Rees 1966). This is mainly due to the relativistic beaming. First the relativistic beaming implies that the observer will see only a small fraction of the emitting region: the constraint on the size of the emitting region is now less severe. Second, the collimation of photons in the same direction reduce the number of potential interactions. Finally the typical $\gamma\gamma$ interaction angle becoming small the photon energy threshold for pair production becomes higher. This theoretical context combined with the observational data gives the possibility to estimate a minimum Lorentz factor $\Gamma_{\rm min}$ for the emitting outflow in GRBs (Lithwick & Sari 2001) or directly a Lorentz factor estimate if the $\gamma\gamma$ cutoff is clearly identified in the spectrum (see Ackermann et al. (2011)).

Severe constraints on the Lorentz factor from Fermi-LAT observations. Since the launch of Fermi in June 2008, the LAT instrument has detected high energy photons above 10 GeV in a few GRBs. The observed γ-ray spectrum often remains consistent with a Band function covering the GBM and LAT spectral ranges without any evidence of a high energy cutoff, that could be identified as a signature of $\gamma\gamma \rightarrow e^+e^-$. This

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extension by Fermi of the observed spectral range upper bound from 10 MeV (e.g. BATSE) to 10 GeV implies constraints on $\Gamma_{\rm min}$ which are much more severe than the ones obtained previously. In a few cases $\Gamma_{\rm min}$ has been estimated to be of the order of 1000 (for example: GRB 080916C – $\Gamma_{\rm min} = 887$ Abdo et al. (2009), GRB 090510 – $\Gamma_{\rm min} = 1200$ Ackermann et al. (2010)). These extreme values put severe constraints on the physics of the central engine which should be able to strongly limit the baryon load in the outflow.

However these $\Gamma_{\rm min}$ values were obtained from a simplified "single zone" model where the space and time dependencies are averaged out. The motivation of this work is to develop a detailed approach taking into account a more realistic treatment of the dynamics.

Computing the $\gamma\gamma$ optical depth. The kernel of our study is the calculation of the $\gamma\gamma$ opacity created by a spherical flash. It is then possible to model the case of a propagating radiating spherical front (representing for example a shock wave) by the succession of many spherical flashes. One of the critical step is the exact calculation of the photon density n_Ω taking into account all the relativistic effects. Before dealing with more complex dynamical configurations within the internal shock framework, the validity of our numerical approach was tested on a simple single-pulse case with a comparison to the previous semi-analytic study of Granot et al. (2008) (see Hascoët et al. (2011) for more details).

2 Application to Internal Shocks

2.1 Internal shocks within a relativistic outflow

The model is applied to the internal shock model, where the whole prompt γ-ray emission is produced by electrons accelerated by shock waves propagating within a relativistic variable outflow. We model the dynamics via a multiple shell model where the successive collisions between shells mimic the propagation of shock waves (Daigne & Mochkovitch 1998). Each collision produces an elementary spherical flash: the simulated light curves are the result of the sum of all flashes. For each high energy photon, the $\gamma\gamma$ opacity is computed by an integration made from its emission location to the observer taking into account the exact radiation field n_Ω produced by all the collisions in the outflow. A previous study of the $\gamma\gamma$ opacity in internal shocks was made by Aoi et al. (2010). However the prescription used to compute $\tau_{\gamma\gamma}$ was still approximate, using the local physical conditions of the outflow where the high energy photon is emitted and applying them to an average formula of $\tau_{\gamma\gamma}$ (as can be found in Lithwick & Sari (2001); Abdo et al. (2009); Ackermann et al. (2010)).

2.2 Minimum Lorentz factor in GRB outflows – The case of GRB 080916C

The first natural application of our model is the estimate of the minimum bulk Lorentz factor $\Gamma_{\rm min}$ in GRB outflows, obtained from the constraint $\tau_{\gamma\gamma}(E_{\rm HE,max}) \simeq 1$, where $E_{\rm HE,max}$ is the highest photon energy detected in the burst. To illustrate this aspect with an example, we applied our approach to the case of one of the four brightest GRBs detected in the GeV range by *Fermi*, i.e. GRB 080916C. The results are shown in Fig. 1. Using our numerical model, a synthetic GRB was generated, which reproduces the main observational features: the total radiated isotropic γ-ray energy ($E_{\rm iso} = 8.8 \times 10^{54}$ ergs between 10 keV and 10 GeV), the spectral properties ($E_{\rm p}$, α, β parameters of the Band function[*]), the envelop of the light curve and a short time-scale variability of 0.5 s in the observer frame. The study is focused on the most constraining time bin (time bin 'b'), during which the highest observed photon energy was $E_{\rm HE,max} = 3$ GeV (16 GeV in the source rest frame): for this reason, only time bins 'a' and 'b' are reproduced in the synthetic GRB. These two intervals correspond to 32 % of the total radiated isotropic equivalent energy. The minimum mean Lorentz factor $\overline{\Gamma}_{\rm min}$ is obtained by requiring that $\tau_{\gamma\gamma}\left(E_{\rm HE,max}\right) \leq 1$ (see Fig. 1, lower panel). With the detailed calculation, we find a minimum mean Lorentz factor $\overline{\Gamma}_{\rm min} = 340$, i.e. a factor 2.6 lower than the value $\overline{\Gamma}_{\rm min} = 887$, which was obtained from an approximate "single zone" model (Abdo et al. 2009). Even more remarkable, the whole initial distribution of the Lorentz factor used in this model of GRB 080916C (from 170 to 700) remains below the "minimum" value of the Lorentz factor derived from single zone models (see Fig. 1, upper left panel).

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[*] We use the values given by Abdo et al. (2009) for time bin 'b'.

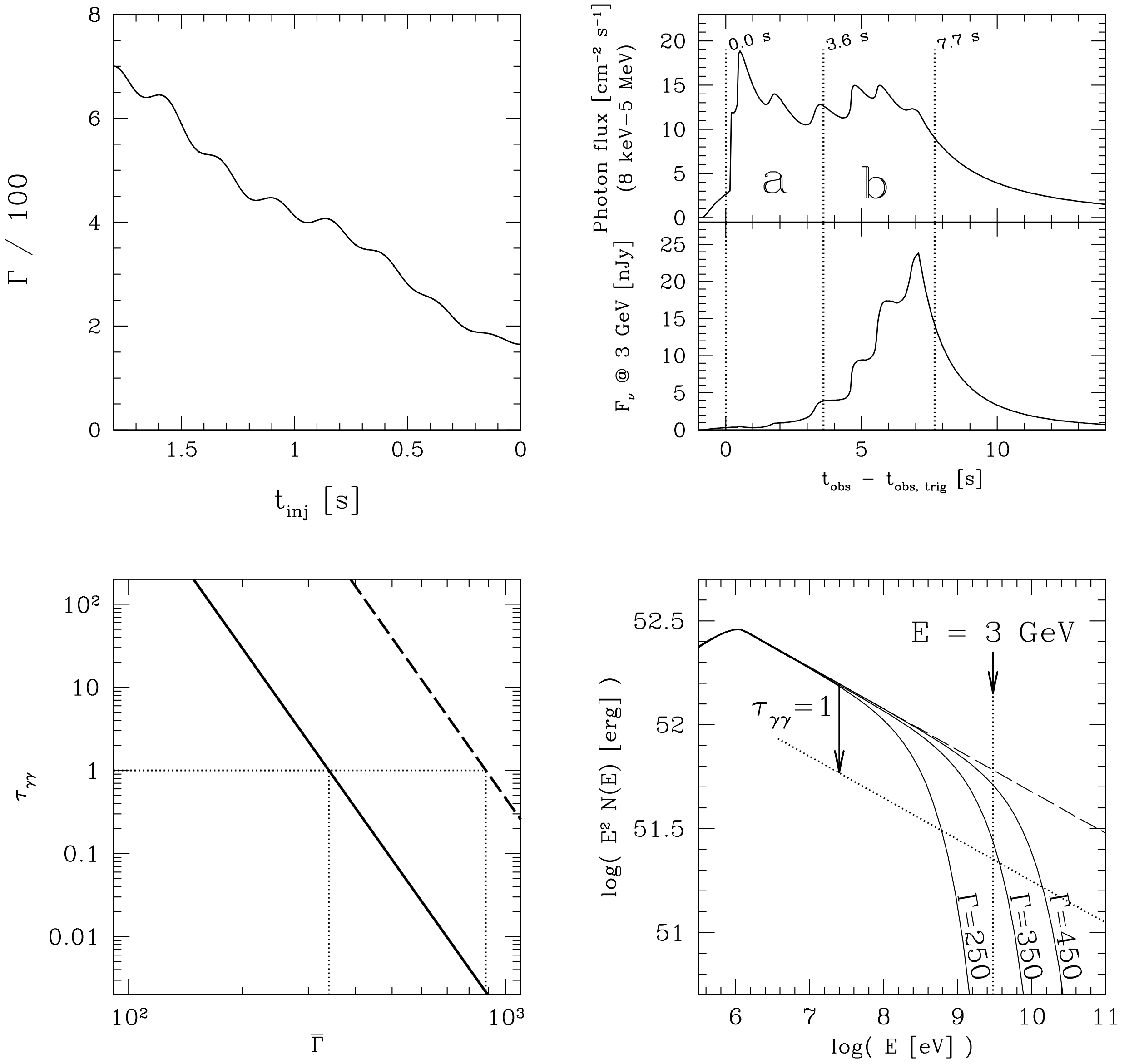

Fig. 1. Minimum Lorentz factor for GRB 080916C. The two first panels are plotted for the limit case leading to $\tau_{\gamma\gamma}(3\,\mathrm{GeV}) = 1$ in time bin 'b', i.e. for a mean Lorentz factor $\overline{\Gamma} = \overline{\Gamma}_{\mathrm{min}} = 340$. *Upper left panel:* initial Lorentz factor distribution in the outflow. *Upper right panel:* γ-ray light curves in the GBM/BGO band (8 keV – 5 MeV, top) and at 3 GeV (bottom). The light curves are plotted as a function of $t_{\mathrm{obs}} - t_{\mathrm{obs,trig}}$, where $t_{\mathrm{obs,trig}}$ is the observer time of the first detected photons. *Lower left panel:* evolution of $\tau_{\gamma\gamma}$ at $E_{\mathrm{HE}} = 3$ GeV against the mean Lorentz factor in the outflow $\overline{\Gamma}$, following our detailed modeling (solid line) and using the average formula from Abdo et al. (2009) (dashed line). *Lower right panel:* time integrated spectrum over time bin 'b' for different mean Lorentz factors (the relative shape of the initial Lorentz factor distribution is kept the same) and reference spectrum without $\gamma\gamma$ annihilation (dashed line). [figure from Hascoët et al. (2011)]

2.3 Is the delayed onset of the GeV emission a signature of the $\gamma\gamma$ opacity ?

The high energy emission (above 100 MeV) detected by *Fermi* in a few bright GRBs often shows a delayed onset compared to the softer γ-ray emission (below 5 MeV). The analysis by Zhang et al. (2011) indicates that such a delayed onset is present in at least 7 in a sample of 17 GRBs detected by *Fermi*-LAT. This feature seems to be common to long and short GRB classes and its origin is debated (Granot et al. 2010). Among the proposed explanations (see e.g. Zou et al. 2009; Li 2010; Toma et al. 2009), the possibility that this delayed onset is induced by a $\gamma\gamma$ opacity temporal evolution effect has already been discussed by Abdo et al. (2009): as the shock wave producing the γ-ray emission expands to larger radii, the opacity seen by the high energy photons evolve from an optically thick to an optically thin regime. The model developed in the present study is well appropriate to investigate this possibility in more details. The synthetic burst used in Fig. 1 to model bins 'a' and 'b' of GRB 080916C gives an example of a delayed onset at 3 GeV induced by an evolving $\gamma\gamma$ opacity. The first pulse is produced at lower radii and in lower Lorentz factor material and is therefore strongly absorbed. For this reason, it is almost suppressed in the 3 GeV light curve, whereas the second pulse is well visible. Note that the model reproduces simultaneously the onset delay of $\simeq$ 5s at high energy, and the short timescale variability of $\simeq$ 0.5s at low energy.

3 Conclusions

The detailed $\gamma\gamma$ opacity calculation model presented in these proceedings is appropriate and accurate to study many aspects and consequences of $\gamma\gamma$ annihilation in GRBs. In the present work we focus on the internal shock model and consider the consequences and signatures that $\gamma\gamma$ opacity could have in GRB observations. The model was validated by comparing our results to a previous semi-analytical study by Granot et al. (2008).

- It is shown how a detailed calculation can predict minimum Lorentz factors Γ_{min} which are lower by a factor of 2-3 compared to a simplified "single zone" model where space and time dependencies are averaged out.
- The temporal evolution of $\tau_{\gamma\gamma}$ during a burst could favor a delay between the MeV and GeV light curves.

Other effects (Hascoët et al. 2011) can be studied with our model:

- The $\gamma\gamma$ cutoff transition can be characterized in time-integrated spectra. It is usually closer to a power-law steepening than to a sharp exponential cutoff. The exact shape of the transition strongly depends on the details of the GRB dynamics.
- For complex GRBs, the $\gamma\gamma$ opacity could suppress the shortest time-scale features in high energy light curves (above 100 MeV).
- If MeV and GeV photons are not produced at the same location (see e.g. Bošnjak et al. (2009); Zou et al. (2011)), $\tau_{\gamma\gamma}$ could be further lowered, reducing even more the constraint on Γ_{min}.

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References

Abdo, A. A. et al. 2009, Science, 323, 1688

Ackermann, M., Asano, K., Atwood, W. B., et al. 2010, ApJ, 716, 1178

Ackermann, M. et al. 2011, ApJ, 729, 114

Aoi, J., Murase, K., Takahashi, K., Ioka, K., & Nagataki, S. 2010, ApJ, 722, 440

Bošnjak, Ž., Daigne, F., & Dubus, G. 2009, A&A, 498, 677

Daigne, F. & Mochkovitch, R. 1998, MNRAS, 296, 275

Granot, J., Cohen-Tanugi, J., & do Couto e Silva, E. 2008, ApJ, 677, 92

Granot, J. et al. 2010, to appear in the Proceedings of "The Shocking Universe - Gamma-Ray Bursts and High Energy Shock phenomena", Venice (Italy), September 14-18, 2009, eprint arXiv:1003.2452.

Hascoët, R., Daigne, F., Mochkovitch, R., & Vennin, V. 2011, submitted to MNRAS, eprint arXiv:1107.5737

Li, Z. 2010, ApJ, 709, 525

Lithwick, Y. & Sari, R. 2001, ApJ, 555, 540

Rees, M. J. 1966, Nature, 211, 468

Toma, K., Wu, X.-F., & Mészáros, P. 2009, ApJ, 707, 1404

Zhang, B.-B., Zhang, B., Liang, E.-W., et al. 2011, ApJ, 730, 141

Zou, Y., Fan, Y., & Piran, T. 2011, ApJ, 726, L2+

Zou, Y.-C., Fan, Y.-Z., & Piran, T. 2009, MNRAS, 396, 1163