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The Build-up of Opacity in Impulsive Relativistic Sources

JOHANN COHEN-TANUGI[1], JONATHAN GRANOT, AND EDUARDO DO COUTO E SILVA
KIPAC, Stanford University, P.O. Box 20450, MS 29, Stanford, CA 94309
[1]*cohen@slac.stanford.edu*

Abstract: Opacity effects in relativistic high-energy γ-ray sources, such as γ-ray bursts (GRBs) or Blazars, can probe the Lorentz factor of the outflow and the distance of the emission site from the source, and thus help constrain the composition of the outflow (protons, pairs, magnetic field) and the emission mechanism. While most previous works consider the opacity in steady state, we study the effects of the time dependence of the opacity to pair production ($\gamma\gamma \to e^+e^-$) in an impulsive relativistic source. This may be relevant for the prompt γ-ray emission in GRBs or flares in Blazars. We present a simple, yet rich, semi-analytic model for the time and energy dependence of the optical depth, $\tau_{\gamma\gamma}$, in which a thin spherical shell expands ultra-relativistically and emits isotropically in its own rest frame over a finite range of radii, $R_0 \leq R \leq R_0 + \Delta R$. This is particularly relevant for GRB internal shocks. We find that in an impulsive source ($\Delta R \lesssim R_0$), while the instantaneous spectrum (which is typically hard to measure due to poor photon statistics) has an exponential cutoff above the photon energy $\varepsilon_1(t)$ where $\tau_{\gamma\gamma}(\varepsilon_1) = 1$, the time integrated spectrum (which is easier to measure) has a power-law high-energy tail above the photon energy $\varepsilon_{1*} \sim \varepsilon_1(\Delta t)$ where Δt is the duration of the emission episode. Furthermore, photons with energies $\varepsilon > \varepsilon_{1*}$ are expected to arrive mainly near the onset of the spike in the light curve or flare, which corresponds to the short emission episode. This arises since in such impulsive sources it takes time to build-up the (target) photon field, and thus the optical depth $\tau_{\gamma\gamma}(\varepsilon)$ initially increases with time and $\varepsilon_1(t)$ correspondingly decreases with time, so that photons of energy $\varepsilon > \varepsilon_{1*}$ are able to escape the source mainly very early on while $\varepsilon_1(t) > \varepsilon$. As the source approaches a quasi-steady state ($\Delta R \gg R_0$), the time integrated spectrum develops an exponential cutoff, while the power-law tail becomes increasingly suppressed.

Introduction, Motivation, and Relevance for GLAST

Opacity effects intrinsic to the source, especially in the GRB prompt emission, are expected to be most relevant in the GLAST LAT energy range (20 MeV to > 300 GeV), and are thus a powerful tool for probing the physics of the source. The optical depth to pair production, $\tau_{\gamma\gamma}$, is usually an increasing function of the photon energy, $E_{\rm ph} = \varepsilon m_e c^2$, and therefore a large optical depth would prevent the escape of high-energy photons from the source, causing a high-energy cutoff in the observed spectrum. The lack of detection of such a high-energy cutoff in the prompt GRB emission has been used to place lower limits on the Lorentz factor of the outflow [1, 2, 3, 4, 5], typically $\Gamma_0 \gtrsim 100$.

We note, however, that $\tau_{\gamma\gamma}$ generally depends both on R_0 and on Γ_0 : $\tau_{\gamma\gamma}(\varepsilon) \propto \Gamma_0^{-2\alpha} R_0^{-1} L_0 \varepsilon^{\alpha-1}$, where $L_\varepsilon = L_0 \varepsilon^{1-\alpha}$ is the isotropic equivalent luminosity at high photon energies (α being the photon index). Therefore, one needs to assume a relation between R_0 and Γ_0 in order to obtain a lower limit on Γ_0. Most works assume $R_0 \sim \Gamma_0^2 c\Delta t$, which gives $\tau_{\gamma\gamma}(\varepsilon) \propto \Gamma^{-2\alpha-2}(\Delta t)^{-1} L_0 \varepsilon^{\alpha-1}$, while the lack of a high-energy cutoff up to some photon energy ε implies $\tau_{\gamma\gamma}(\varepsilon) < 1$. This, in turn, provides a lower limit on Γ_0 since both the variability time Δt, the photon index α, and L_0 can be measured directly. The latter is given by $L_0 = 4\pi d_L^2 (1+z)^{\alpha-2} \varepsilon^{\alpha-1} F_\varepsilon$, where F_ε is the observed flux, while z and d_L are the redshift and luminosity distance. However, the relation $R_0 \sim \Gamma_0^2 c\Delta t$ does not hold for all models of the prompt GRB emission. Therefore, we shall adopt a more model-independent approach and not make this assumption.

GLAST is likely to detect the high-energy cutoff due to pair opacity, which would actually determine $\Gamma_0^{2\alpha} R_0$, rather than just provide a lower limit for it. Furthermore, in GRBs the outflow Lorentz factor Γ_0 may be constrained by the time of the afterglow onset [6, 7, 8] so that if GLAST detects the high-energy pair opacity cutoff, the radius of emission R_0 could be directly constrained, thus helping to test the different GRB models. This, however, requires a reliable way of identifying the observed signatures of pair opacity, which is one of the main motivations for this work.

The leading model for the prompt emission in GRBs features internal shocks [9] due to collisions between shells that are ejected from the source at ultra-relativistic speeds ($\Gamma_0 \gtrsim 100$). The shells are typically quasi-spherical, i.e. their properties do not vary a lot over angles $\lesssim$ a few Γ_0^{-1} around our line of sight. Under the typical physical conditions that are expected in the shocked shells, all electrons cool on a time scale much shorter than the dynamical time (the shell shock crossing time), and most of the radiation is emitted within a very thin cooling layer just behind the shock front. Thus, our model of an emitting spherical relativistic thin shell is appropriate for the internal shocks model.

The Model: an emitting spherical relativistic thin shell

The emission is assumed to turn on at some finite radius R_0, and turn off at $R_0 + \Delta R$, where $\Delta R \sim R_0$ is expected for internal shocks. This corresponds to a single pulse in the observed light curve. The emission is assumed to be isotropic in the co-moving frame of the emitting shell, and uniform over the spherical shell. The co-moving spectral emissivity is assumed to have a power law dependence on radius and photon energy, $L'_{\varepsilon'} \propto (\varepsilon')^{1-\alpha} R^b$. The Lorentz factor of the shell is assumed to be a power law with radius, $\Gamma^2 \propto R^{-m}$. We perform a detailed semi-analytic calculation of the optical depth to pair production, which improves on previous works by first calculating the photon field at each point in space and time, and then integrating the contribution to the optical depth along the trajectory of each test photon. Finally, we calculate the unattenuated flux seen by a distant observer as a function of time and photon energy.

The flux seen by an observer at infinity, i.e. at a distance $D \gg R_0 + \Delta R$, is calculated by integrating over the equal arrival time surface (EATS-I) – the locus of emission points from which photons reach the observer at the same time T. For a coasting shell ($m = 0$), EATS-I is an ellipsoid. Following [10], the observed (unattenuated) flux is given by:

$$\begin{aligned} F_\varepsilon(T) &= \frac{1}{4\pi D^2} \int \delta^3 e^{-\tau_{\gamma\gamma}} dL'_{\varepsilon'} \\ &= \frac{1}{8\pi D^2} \int_{y_{\min}}^{y_{\max}} dy \frac{d\cos\theta_{t,0}}{dy} \delta^3(y) \times \\ &\times \quad L'_{\varepsilon'}(y) e^{-\tau_{\gamma\gamma}(y)} \,, \end{aligned} \tag{1}$$

where $\delta \equiv \varepsilon/\varepsilon'$ is the Doppler factor, $\theta_{t,0}$ is the angle of emission (measured from the line of sight), and $y \equiv R_{t,0}/R_L$ is the normalized radius, where $R_L(T)$ is the largest radius on the EATS-I (which is along the line of sight). The integration is done along EATS-I, where $y_{\min}(T) = \min[1, R_0/R_L(T)]$ and $y_{\max}(T) = \min[1, (R_0 + \Delta R)/R_L(T)]$. The exponential factor represents the simple assumption that photons which pair produce do not reach the observer (the generated pairs and their further interactions are ignored in this simple treatment).

Next, we compute the optical depth $\tau_{\gamma\gamma}$ by integrating the contributions to the opacity along the trajectory of each test photon, that is emitted at some lab frame time t_0, angle $\theta_{t,0}$, and radius $R_{t,0}$. This requires calculating the photon field at each point along the test photon trajectory, which is done by integrating along the equal arrival time surface of photons to that particular place and time (EATS-II). This naturally divides into three cases, as is illustrated in Figure 1. The full derivations are much too long to fit here, and can be found in [11].

Preliminary Results and Conclusions

This work is in progress and we show here only preliminary results. Figure 2 shows results for model parameter values that are relevant for GRB internal shocks: $m = 0$ (coasting shells) $b = 0$ (total comoving luminosity independent of radius),

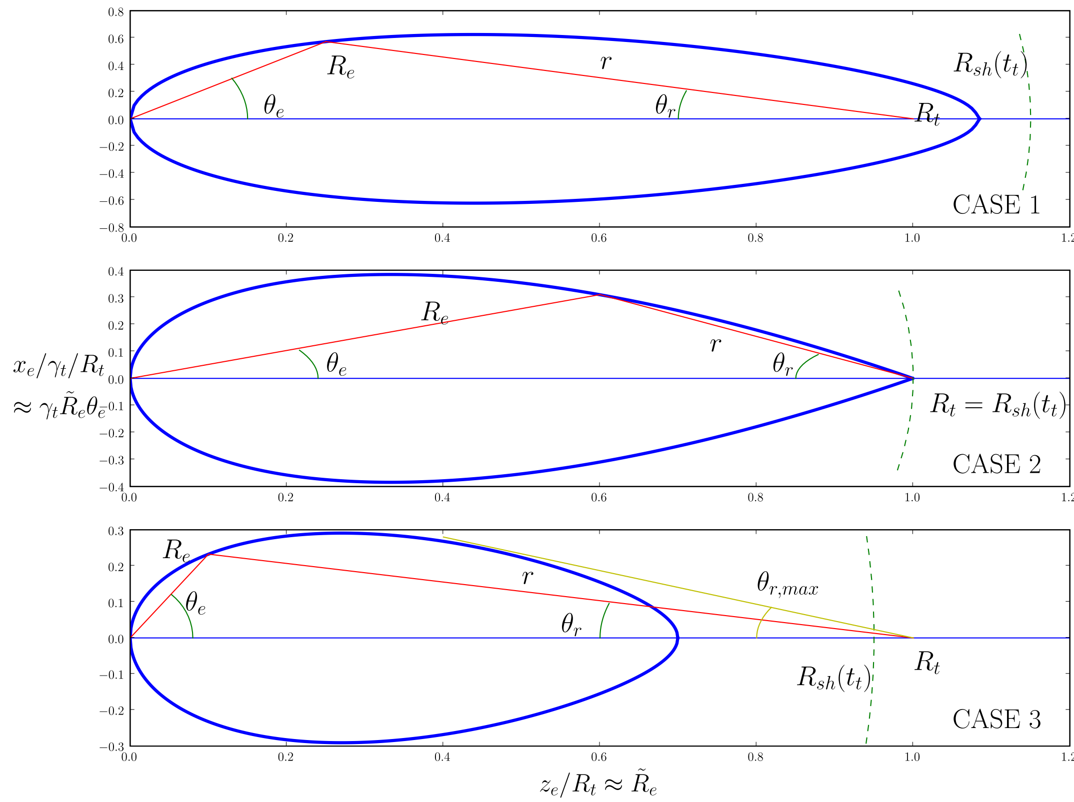

Figure 1: The three possible cases for the equal arrival time surface of photons to a point along the trajectory of a test photon (EATS-II). If the test photon is emitted at $\Gamma(R_{t,0})\theta_{t,0} > 1$, then it initially lags behind the emitting shell (case 1), and only later catches-up with it (case 2) and overtakes it (case 3). For $\Gamma(R_{t,0})\theta_{t,0} < 1$ the test photon is immediately ahead of the shell (case 3).

$\Delta R/R_0 = 1$ (reasonably impulsive), and $\alpha = 2$ (equal energy per decade in $\varepsilon = E_{\rm ph}/m_e c^2$). At high photon energies, $\varepsilon > \varepsilon_{1*}$, the time integrated spectrum steepens but asymptotically approaches a power-law. Furthermore, photons above this spectral break ($\varepsilon > \varepsilon_{1*}$) arrive mainly at early times, near the onset of the spike in the light curve.

More generally, we find that in impulsive ($\Delta R/R_0 \lesssim 1$) relativistic sources, pair production within the source results in a steeper power law at high photon energies in the time integrated (over a spike or pulse in the light curve) spectrum. This power law high-energy tail becomes increasingly suppressed in the quasi-steady state limit ($\Delta R/R_0 \gg 1$), and is replaced by an exponential cutoff. The instantaneous spectrum (which is usually very hard to measure) also has a sharper high-energy cutoff than the time integrated spectrum. Furthermore, in impulsive sources, photons above the spectral break due to pair production should arrive mainly near the onset of a pulse or spike in the light curve. These spectral and temporal features should provide a clear observational signature of pair opacity in impulsive relativistic sources, which if detected by GLAST would enable very interesting constraints to be put on the Lorentz factor of the outflow and on the radius of the emission site, which would in turn help constrain the composition of the outflow.

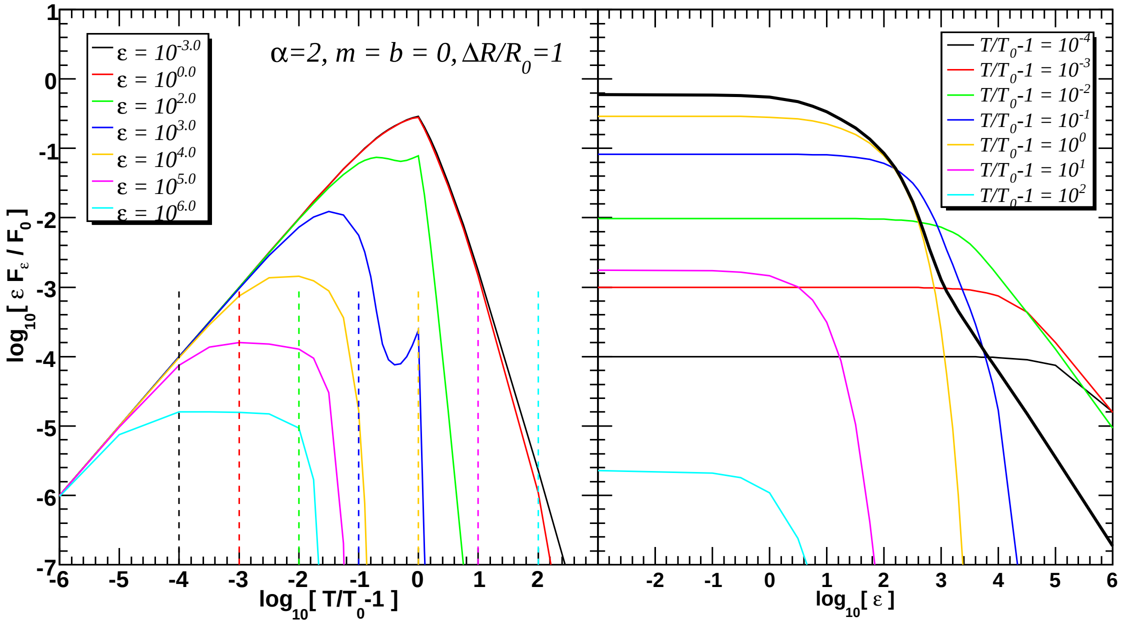

Figure 2: **Left panel**: Lightcurves for different normalized photon energies, $\varepsilon = E_{\rm ph}/m_e c^2$, using model parameters relevant for GRB internal shocks; T_0 is the observer time at which the first photon reaches the observer (it is emitted along the line of sight, and no other photon can catch-up with it). The vertical dashed lines show the times at which the instantaneous spectra are shown in the *right panel*, using the same colors. **Right panel**: instantaneous spectra (*thin lines*) and time integrated spectrum (*thick line*).

References

[1] J. H. Krolik, and E. A. Pier, *ApJ*, **373**, pp. 277 (1991).

[2] E. E. Fenimore, R. I. Epstein, and C. Ho, *A&A Suppl. Ser.*, **97**, pp. 59 (1993).

[3] E. Woods, and A. Loeb, *ApJ*, 1995, 453, pp. 583.

[4] M. G. Baring, and A. K. Harding, *ApJ*, **491**, 663 (1997)

[5] Y. Lithwick, and R. Sari, *ApJ*, **555**, pp. 540 (2001).

[6] A. Panaitescu, and P. Kumar, *ApJ*, **571**, 779 (2002).

[7] W. H. Lee, E. Ramirez-Ruiz, and J. Granot, *ApJ*, **630**, L165 (2005).

[8] E. Molinari, et. al., *A&A* in press 2007 (`astro-ph/0612607`).

[9] M. J. Rees, and P. Mészáros, *ApJ*, **430**, L93 (1994).

[10] Granot, J. 2005, ApJ, 631, 1022

[11] J. Cohen-Tanugi, J. Granot, and E. do Couto e Silva, 2007, in preparation