Opacity Build-up in Impulsive Relativistic Sources

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Outline of the Talk:

- **Motivation** (GRBs, flares in Blazars, GLAST)
- Description of the **model**
- Outline of the **calculation**
- **Results**: opacity, light curves & spectra
- **Some intuition**
- **Conclusions**
Motivation (1):

- We consider the opacity to pair production ($\gamma \gamma \rightarrow e^+e^-$) within the source (flaring region).
- Opacity effects are expected to be important in GLAST LAT energy range ($\sim 20 \text{ MeV} - 300 \text{ GeV}$).
- Above some photon energy $\varepsilon_1$, $\tau_{\gamma\gamma} > 1$ & the spectrum is expected to cut off exponentially.
- Lack of such a cutoff up to an observed photon energy $\varepsilon_{\text{max}} \Rightarrow \Gamma \sim 100[L_{0,52}(\varepsilon_{\text{max}})^{\alpha-1}/R_{13}]^{1/2\alpha}$ where $\varepsilon = E_{\text{ph}}/m_e c^2$ and $L_\varepsilon = L_0 \varepsilon^{1-\alpha}$.
- This was used to put a lower limit on assuming $R \sim \Gamma^2 c \Delta t$ where $\Delta t = \text{observed variability time}$.
Motivation (2):

- Observing the high energy cutoff due to $\tau_\gamma$ will determine $\Gamma^2\alpha R$ (instead of just a lower limit)
- Together with an independent estimate of $\Gamma$ this can determine $R$ and check if indeed $R \sim \Gamma^2 c \Delta t$
- Some sources are highly variable, suggesting impulsive emission (GRBs, flares in Blazars,...)
- Initially there is no photon field & the opacity builds-up with time $\Rightarrow$ even $\varepsilon > \varepsilon_1$ (steady state)
- Photons can initially escape, as long as $\varepsilon_1(t) > \varepsilon$
- $\Rightarrow$ a distinct temporal & spectral signature
Simple (yet rich) Semi-Analytic Model

- Ultra-relativistic ($\Gamma \gg 1$) spherical thin ($\Delta \ll R/\Gamma^2$) shell emits in a finite interval $R_0 \leq R \leq R_0 + \Delta R$

- Isotropic emission in the shell co-moving frame

- For simplicity $\Gamma^2 \propto R^{-m}$, $L' \propto (\epsilon')^{1-\alpha} R^b$ is assumed while the formalism is more general

\[ \gamma \gamma \rightarrow e^+ e^- \]

Expanding shell

- Impulsive: $\Delta R \leq R_0$
- Quasi-steady: $\Delta R \gg R_0$

Observer at infinity

Corresponds to a single flare/spike in light curve

Graph showing normalized flux vs. $(T/T_0) - 1$
Calculation of the observed Flux:

- Flux calculation: integration over the equal arrival time surface of photons to the observer
- The photon field is calculated at all space & time
- The pair-production optical depth is calculated by integrating along the trajectory of each photon

**Equal arrival time surface:**

\[
T = t - \frac{R}{c} \cos \theta
\]

\[
t = \int_0^R dR \frac{dR}{\beta c}
\]

\[T = \text{photon arrival time to observer}\]
\[\theta = \text{emission angle from the l.o.s.}\]
\[t = \text{emission time (in lab frame)}\]

\[
F_{\epsilon}(T) = \frac{2\gamma_0 L'_{\epsilon}}{4\pi D^2} \left( \frac{T}{T_0} \right)^{\frac{2b-m(\alpha+1)}{2(m+1)}} \int_{y_0}^1 dy \left( \frac{m+1}{m+y^{-m-1}} \right)^{2+\alpha} y^{b-1} - \frac{m(\alpha+1)}{2} e^{-\gamma \gamma}
\]
Calculating the $\gamma \gamma \rightarrow e^+ e^-$ Optical Depth

\[ \tau_{\gamma \gamma}(R_{t,0}, \theta_{t,0}, \epsilon_i) = \int ds \int d\epsilon_i \int d\Omega_i \sigma^* \left[ \chi(\epsilon_i, \epsilon_i, \mu_{t,i}) \right] (1 - \mu_{t,i}) \frac{d n_i}{d\epsilon_i d\Omega_i} \]

- $s = \text{path length along test photon trajectory}$
- $\epsilon_i, \epsilon_i = \text{energies of test photon and potentially interacting photon in units of } m_e c^2$
- $\mu_{t,i} = \text{cosine of the angle between the directions of the two photons}$
- $\Omega_i, n_i = \text{solid angle and number density of the potentially interacting photons}$
- $\sigma^* = \text{the pair production cross section}$
- $\chi = \text{center of momentum energy of photons in units of } m_e c^2$
Calculating the $\gamma\gamma \to e^+e^-$ Optical Depth

At each point along the test photon trajectory the local photon field is calculated by integrating along the equal arrival time surface to that space-time point: EATS-II
Results: Light Curves & Instantaneous Spectra

\[ \frac{\varepsilon F_\varepsilon}{F_0} \]

\[ \varepsilon = 10^{3.0}, 10^{4.0}, 10^{5.0}, 10^{6.0} \]

\[ T_0 = \text{time when first photon reaches the observer at infinity} \]

\[ T_0 / T_0 = 10^{0.1} \]

\[ \alpha = 2, m = b = 0, \Delta R/R_0 = 1 \]

\[ T/T_0 = 10^{0.1} \]

1 GeV
Time Integrated Spectrum: Power law High Energy Tail

GLAST:
- GBM
- LAT

\[ \alpha = 2, \ m = 0, \ b = 0 \]

\( 8 \text{ keV} \)

\( 300 \text{ GeV} \)

\( \frac{\varepsilon F_{\varepsilon}}{F_0} \)

\( \frac{R}{R_0} = 0.01 \)

\( \frac{R}{R_0} = 0.1 \)

\( \frac{R}{R_0} = 1 \)

\( \frac{R}{R_0} = 10 \)

\( \frac{R}{R_0} = 100 \)

1 MeV, 25 MeV, 1 GeV
Temporal signature:
High energy photons, above the break in time integrated spectrum escape mainly near the onset of a flare or spike in the light curve.

The opacity builds-up & saturates on a dynamical time scale.
Validity of the Model Assumptions:

- **Thin Shell**: in internal shocks $t_{\text{cool}} \ll t_{\text{dynamic}} \Rightarrow$ thin cooling layer behind the shock
- **Spherical geometry**: reasonably valid in GRBs; should not qualitatively affect the main results
- **Power law emission spectrum**: only marginally valid for GRBs \( \Rightarrow \) will be generalized
- **Neglecting external opacity**: valid for GRBs; not so clear how valid in Blazar flares (but can be distinguished by lack of $\tau_{\gamma\gamma}$ time dependence)
- **Single spike/flare**: reasonably valid for spikes after quiescent period; vicinity to previous spike or flare would effect manly high energies $\varepsilon \gg \varepsilon_{1*}$
Conclusions:

- Opacity effects can constrain the emission radius & outflow Lorentz factor $\Rightarrow$ composition as well ($e^\pm/p/B$)
- We developed a semi-analytic time dependent model for a single flare/spike in the light curve
- Relevant for GRBs & perhaps also flares in Blazars
- $\gamma\gamma \to e^+e^-$ opacity has distinct observable signatures:
  - Power law high-energy tail in the time integrated spectrum (instantaneous spec.: exponential cutoff)
  - Photons above the spectral break would arrive mainly near the onset of spikes in light curve
- We plan to improve our model - use a more realistic low energy spectrum & compare with GLAST data
Why is there an exponential cutoff in the spectrum of a (quasi-) steady source?

- If the emission and “absorption” are in the same region (e.g. by the same material), then photons can escape only from a thin layer of width $\sim R/\tau$ at the edge of the emitting region: $L_{\text{esc}} \sim L_{\text{emit}}/\tau$

- For $\gamma\gamma \rightarrow e^+e^-$ attenuation occurs also outside of the emitting region $\Rightarrow \tau_2 \sim \tau_1 \sim \sigma n_{\text{ph}} R$ for steady sources $\Rightarrow$ exponential cutoff

- This assumes a $\sim$uniform $n_{\text{ph}}$ in emission region $\Rightarrow$ requires reasonably localized emission

- Holds for a relativistic source