How may GLAST Help Solve some GRB Mysteries Raised by Swift

Jonathan Granot
KIPAC @ Stanford


First GLAST Symposium, February 7, 2007, Stanford
Outline of the Talk:

- Early X-ray afterglow of Swift GRBs: flat decay phase
  - brief outline of possible explanations & implications
  - GLAST could test the models & effect implications
- X-ray flares: from same mechanism as prompt GRB?
  - GLAST could probe emission site & mechanism
- Opacity effects in prompt GRB emission / X-ray flares
  - Time dependence: helps distinguish between models & effects shape of high-energy cutoff in spectrum
  - Results applicable to impulsive relativistic sources
- Conclusions
Early X-ray Afterglows from Swift:

- Rapid decay $t^{-5} - t^{-3}$
- Flat part
- "usual" Post jet break $t^{-1.5}$
- Tail of prompt emission
- $\sim 10^{2.5}$ s
- $\sim 10^4$ s

(Vaughan et al. 2006)

(O’Brien et al. 2006)
Possible Explanations for Early Flat Decay

- **Energy injection** into afterglow: *(Nousek et al. 06)*
  - I. Continuous relativistic wind $L \propto t^{-0.5}$ (magnetar?)
  - II. Slower material ejected during the prompt GRB gradually catches up the decelerating afterglow shock

- Afterglow efficiency increases with time *(varying shock micro-physics parameters; JG, Königl & Piran 06)*

- Observer outside emitting region *(JG & Eichler 06)*

(JG, Ramirez-Ruiz & Perna 05)
Possible Explanations for Early Flat Decay

- **Energy injection** into afterglow: (Nousek et al. 06)
  - I. Continuous relativistic wind $L \propto t^{-0.5}$ (magnetar?)
  - II. Slower material ejected during the prompt GRB gradually catches up the decelerating afterglow shock

- Afterglow efficiency increases with time (varying shock micro-physics parameters; JG, Königl & Piran 06)

- Observer outside emitting region (JG & Eichler 06)

- Two component jet:
  - Wide jet: $\Gamma_0 \sim 20-50$
  - Narrow jet: $\Gamma_0 > 100$

$$t_{\text{dec}} \propto \Gamma_0^{-2(4-k)/(3-4)}$$ for $\rho_{\text{ext}} \propto r^{-k} \Rightarrow t_{\text{dec},\text{n}} \ll t_{\text{dec},\text{w}}$$
Implications for $\gamma$-ray Efficiency

- $\varepsilon_\gamma = E_\gamma / E_0$, $\varepsilon_\gamma / (1 - \varepsilon_\gamma) = \kappa f$; $\kappa = E_\gamma / E_k(t)$, $f = E_k(t) / E_{k,0}$
- $\kappa \sim 1$ from the X-ray afterglow flux at $t = 10$ hr
Implications for $\gamma$-ray Efficiency

- $\varepsilon_\gamma = E_\gamma/E_0$, $\varepsilon_\gamma/(1-\varepsilon_\gamma) = \kappa f$; $\kappa = E_\gamma/E_k(t)$, $f = E_k(t)/E_{k,0}$
- $\kappa \sim 1$ from the X-ray afterglow flux at $t = 10$ hr
- $f \geq 10$ if flat decay is energy injection: $\varepsilon_\gamma \geq 0.9$
- If the flat decay phase is due to an increase in the afterglow efficiency then $f \sim 1$ & $\varepsilon_\gamma \sim 0.5$
- If also $E_k(t = 10$ hr$)$ is underestimated (e.g., $\xi_e \sim 0.1$ instead of 1) then possibly $\kappa \sim 0.1$ & $\varepsilon_\gamma \sim 0.1$
- $\Rightarrow$ a typical afterglow kinetic energy $\geq 10^{52}$ erg ($\geq 10^{53}$ erg) for a uniform (structured) jet
- **GLAST** might find a larger $E_\gamma$ $\Rightarrow$ higher $\varepsilon_\gamma$
- Models differ in **GLAST** range (SSC component)
X-ray Flares

- Temporal & spectral properties similar to prompt GRB
- The emission site & mechanism is similarly uncertain
- GLAST observations can help solve such questions (SSC component, opacity effects)

Best example of a flare in the X-ray afterglow
(Falcone et al. 2006)
**Pair Opacity: Time Dependence**

*Work in progress, with J. Cohen-Tanugi & E. do Couto e Silva*

- Above some photon energy $\varepsilon_1$, $\tau_{\gamma\gamma} > 1$ at the source & the spectrum cuts off exponentially.

- Lack of such a cutoff up to an observed photon energy $\varepsilon_{\text{max}} \Rightarrow \gamma \geq 100[L_{0.52}(\varepsilon_{\text{max}})^\alpha/R_{13}]^{1/2(1+\alpha)}$
  
  Where $\varepsilon = E_{\text{ph}}/m_e c^2$, $L_\varepsilon = L_0 \varepsilon^{-\alpha}$

- In some models the emission is impulsive (e.g. internal shocks), rather than quasi-steady state.

- Initially there is no photon field & the opacity builds-up with time $\Rightarrow$ even $\varepsilon > \varepsilon_1(\text{steady state})$ 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 \(\gamma^2 \propto R^{-m}, L'_{\epsilon}, \propto (\epsilon')^{-\alpha}R^b\) is assumed while the formalism is more general
- The thin shell approximation is valid for GRB internal shocks (fast cooling: thin cooling layer)
- The photon field is calculated at all space & time
- The pair-production optical depth is integrated along the trajectory of each photon
Calculating the $\gamma \gamma \rightarrow e^+e^-$ Optical Depth

$F(\gamma_t,0,\theta_t,0) = \int ds \int d\varepsilon_i \int d\Omega_i \sigma^* [\chi(\varepsilon_i,\varepsilon_i,\mu_{i,t})](1-\mu_{i,t}) \frac{dn_i}{d\varepsilon_id\Omega_i}$

$s$ = path length along test photon trajectory

$\theta_{t,0}$ = initial angle between the test photon direction and the radial direction

$\mu_{t,i}$ = cosine of the angle between the directions of the two photons

$\chi$ = center of momentum energy of photons in units of $m_ec^2$

$\Omega_i$ = solid angle of the photons that can potentially interact with the test photon

$n_i$ = number density of these photons

$\sigma^*$ = the cross section for pair production
Results: optical depth

Fixed radius

Equal arrival time surfaces

Fixed angle

$\Delta R = R_0$

$\Delta R \gg R_0$
Light Curves & Spectra

The power law tail is more pronounced for larger $\Delta R / R_0$.
Conclusions:

- High energy spectral components in the GLAST range may help pin down the origin of the early shallow decay phase, as well as the emission mechanism in the prompt GRB & X-ray flares.

- Opacity build-up in impulsive relativistic sources
  - Power law high-energy tail instead of the exponential cutoff in steady state models
  - Photons above the spectral break would arrive mainly near the onset of spikes in light curve