The Flat Decay Phase in the Early X-ray Afterglows of Swift GRBs

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Includes work from the papers:

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Outline of the Talk:

- Short description of Swift & its main findings
- Swift finds a flat decay phase in the early X-ray afterglow of many GRBs: $F_X <$ was expected
- Possible Explanations:
  - Energy injection into the afterglow shock
  - Viewing angle slightly outside emitting region
  - Afterglow efficiency increases with time
  - A two component jet model
- Possible implications:
  - The efficiency of the gamma-ray emission
  - The kinetic energy in the afterglow shock
- Conclusions
Swift Observatory
launched: November 20, 2004

Orbit
600 km x 28° inclination

Data Downlinks
TDRSS rapid (2 kbps)
ASI Malindi gnd station

Operations
Ops Center @ Penn State
Science Center @ GSFC

BAT
New CdZnTe detector
~100 GRBs/yr

XRT
Arcsec GRB positions
CCD spectroscopy

UVOT
Sub-arcsec positions
Grism spectroscopy

Spacecraft
Autonomous slews 20-75s
Swift’s Main Discoveries so far:

- **Short-hard GRBs**
  - First detection of their afterglows
  - redshifts \((z \sim 0.2-0.7) \Rightarrow\) energy & event rate
  - Host galaxies (different from long-soft GRBs)
  - Constraints on contemporaneous supernova

- **Early afterglow emission**
  - Flat decay phase in many X-ray light curves
  - X-ray flares in many cases
  - Dim early optical emission (reverse shock)

- **GRBs at high redshifts** \((z = 6.29) \Rightarrow\) cosmology

- Resolved rise time of SGR 1806-20 giant flare
Early X-ray Afterglows from Swift:

- Early X-ray Afterglows from Swift:

(Vaughan et al. 2006)

(O’brien et al. 2006)
X-ray afterglow light curves (Nousek et al. 2006)

Best example of a flare in the X-ray afterglow (Falcone et al. 2006)
Possible Explanations for Early Flat Decay

1. Energy Injection into the Afterglow Shock
   - Type I: continuous relativistic wind:
     - The source must remain active for up to a few hours with $L \propto t^{-0.5}$
     - might be possible for a magnetar (Usov 1992)
   where $L \propto t^0 \rightarrow t^{-2}$ (Dai & Lu 1998; Dai 2004)
The magnetar model is able to reproduce the right energy scale and time scale.

\[
E \approx 5 \times 10^{52} \left( \frac{\Omega}{10^4 \text{s}^{-1}} \right)^2 \text{erg}
\]

\[
\tau \approx 20 \left( \frac{\Omega}{10^4 \text{s}^{-1}} \right)^{-2} \left( \frac{B}{3 \times 10^{15} \text{G}} \right)^{-2} \text{s}
\]

It has many potential problems:

- How to launch a collimated relativistic jet
- What sets the GRB duration & energy
- Hard to explain the observed diversity
- How to avoid collapse into a black hole
Type II Energy Injection:

- The outflow is ejected within the duration of the GRB (typically tens of seconds)
- It naturally has some spread in Lorentz factors
- The outflow naturally sorts itself out in order of increasing velocity - faster ahead of slower
- Slower outflow takes longer to catch up with the afterglow shock & deposit its energy
- \[ \Rightarrow \] gradual energy injection \((Sari \ & \ Mészáros \ 00)\) until the slower outflow that carries most of the energy catches up with the afterglow shock
has predictions for the evolution of the broad band spectrum & the light curves

forward shock
CD
reverse shock

1. Unperturbed ext. medium
2. Shocked external medium
3. Shocked ejecta
4. Freely expanding ejecta

(Sari & Mészáros 2000)
Implications of Type II Energy Injection:
Distribution of energy with ejecta 4-velocity

(Granot & Kumar 2006)
2. Viewing angle outside the emitting region

- Smaller $F$, $f$, $E_{\text{peak}}$?

(Eichler & Granot 2006)
Implications of viewing angle interpretation:

- If the regions of prominent **gamma-ray** and **afterglow** emission **coincide**, then a smaller typical photon energy, fluence and peak flux are expected: X-ray flashes (Yamazaki et al. ‘02, 03, 04)

- This does **not show up** in the data: it might suggest that **these two regions do not coincide**

- Along some lines of sight there is a bright gamma-ray emission but dim afterglow emission $\Rightarrow$ high gamma-ray efficiency and/or low afterglow efficiency
3. Increase in afterglow Efficiency:

(Granot, Königl & Piran 2006)

- The energy in the afterglow shock is constant.
- The emission is from along our line of sight.
- The afterglow efficiency initially increases with time, due to a change in one or more of:
  - $\varepsilon_e = \text{fraction of energy in relativistic electrons}$
  - $\varepsilon_B = \text{fraction of energy in the magnetic field}$
  - $\xi_e = \text{fraction of electrons that are relativistic}$
- The shock microphysics parameters eventually saturate at some asymptotic values.
- This may have interesting implications for relativistic collisionless shocks.
Inferring the Kinetic Energy:

\[ F_{\nu > \text{max}(\nu_m, \nu_c)} \propto \xi_e^{2-p} (1+Y)^{-1} \varepsilon_e^{p-1} (\varepsilon_B/\varepsilon)^{(p-2)/4} E_{k,iso}^{(p+2)/4} t^{(2-3p)/4} \nu^{-p/2} \]

\[ E_{k,iso} \propto \xi_e^{4(p-2)/(p+2)} (1+Y)^{4/(p+2)} \varepsilon_e^{-4(p-1)/(p+2)} \varepsilon_B^{-(p-2)/(p+2)} \]

- Flux independent of external density \((\nu > \nu_m, \nu_c)\)
- Weak dependence on \(\varepsilon_B\) which is very uncertain
- \(E_{k,iso}\) inferred from \(F_X(10\text{hr})\) pre-Swift (for \(\xi_e = 1\))

Problems with this method:

- Typically \(\varepsilon_B \ll \varepsilon_e \Rightarrow (1+Y) \sim (\varepsilon_e/\varepsilon_B)^{1/2}\),
- \(F_\nu \propto (\varepsilon_e)^{-2(2p-3)/(p+2)} (\varepsilon_B)^{-p/(p+2)}\) (larger \(\varepsilon\)-dependence)
- There is a degeneracy: the observed \(F_\nu\) is not affected by \((E,n) \rightarrow (E,n)/\xi_e\), \((\varepsilon_e, \varepsilon_B) \rightarrow \xi_e(\varepsilon_e, \varepsilon_B)\)
  for \(m_e/m_p < \xi_e \leq 1\) (Eichler & Waxman 2005)
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 the early flat decay phase is interpreted as energy injection into afterglow shock: $\varepsilon_\gamma \geq 0.9$
- Such high efficiencies are very hard to produce
- 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 $E_k(t = 10 \text{ hr})$ 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 $\geq 10^{52} \text{ erg}$ ($\geq 10^{53} \text{ erg}$) for a uniform (structured) jet
4. A Two Component Jet:
(Granot, Königl & Piran 2006)

- **Motivation:**
  - In the collapsar model the wide jet is produced by the cocoon (Ramirez-Ruiz et al. 2002)
  - Neutron decoupling in a hydromagnetically driven neutron rich jet (Vlahakis et al. 2003)

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

- \( E_{\text{iso,w}} < E_{\text{iso,n}} \) \& \( E_w > E_n \) \( \Rightarrow \) lowers the required \( \gamma \)-ray efficiency \( \varepsilon_\gamma \) (Peng, Königl & Granot 2005)
Afterglow light curves for a two component jet:

- $E_w > E_n$ is required for the wide jet to dominate the flux at late times.
- $E_{iso,w} < E_{iso,n}$ is in order to lower the required $\varepsilon_\gamma$.

(Peng, Königl & Granot 2005)
The X-ray afterglow of GRB 050315 requires that $f = \frac{E_{iso,w}}{E_{iso,n}} \gtrsim 30$ and more generally $f > 1$ so that the required gamma-ray efficiency is not lowered.

$E_{w}/E_{n} \gtrsim 100$ is challenging for theoretical models.

Two component jet: Explaining the flat decay

(Granot, Königl & Piran 2006)
Simultaneous Optical light curves

- The optical light curves do not show a similar flat decay phase or a similar steepening at its end.
- This is problematic for most models.

(Panaitescu et al. 2006)
Conclusions:

- There are different possible explanations for the early flat decay phase in the X-ray afterglows.
- The different explanations may potentially be distinguished via multi-wavelength observations.
- There are potentially interesting implications for:
  - The gamma-ray efficiency
  - The afterglow kinetic energy
  - Collisionless relativistic shocks
- A lot of work still remain to be done