Non–standard GRB Afterglows

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A "standard" afterglow

- $\sim 10^{51}$ erg injected into a collimated flow
- Jet opening angle $\theta_0 \sim$ a few deg
  (observer near jet axis)
- Shock driven into ambient medium; $\Gamma \gg 1$
  Uniform density / Stellar Wind: $r^{-2}$
- Particle acceleration $\Rightarrow N(\gamma_e) \propto \gamma_e^{-p}$ $p > 2$; $p \sim 2.2$
- Magnetic Field build–up
- Synchrotron emission $\Rightarrow$ Afterglow
- Light curve: power–law decline
  (rise while $v < v_m$ or $v_a$)
- Jet Deceleration $\Rightarrow$ lateral expansion
  when $\Gamma < 1/\theta_0$, break in the light curve

$\varepsilon_e$: Fraction of thermal energy in power–law electrons
$\varepsilon_B$: Fraction of thermal energy in magnetic field

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Constant in time

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Wijers, Rees and Meszaros 1997
Waxman 1997
Sari, Piran and Narayan 1998
Rhoads 1999
Sari, Piran and Halpern 1999
Predictions of the standard model

\[ F_v \propto v^{-\alpha} t^{-\beta} \]

Before "jet break"

\[ F_m \equiv F(v_m) = \text{const.} \]
\[ v_m \propto t^{-3/2} \quad v_c \propto t^{-1/2} \]
\[ v_m < v < v_c : \ \alpha = 3(p-1)/4 \ ; \ \beta = (p-1)/2 \]
\[ v > v_c : \ \alpha = (3p-2)/4 \ ; \ \beta = p/2 \]
\[ \alpha = 3\beta/2 \]
\[ \alpha = 3\beta/2 - 1/2 \]

After "jet break"

\[ F_m \propto t^{-1} \]
\[ v_m \propto t^{-2} \]
\[ v_c = \text{const.} \]
\[ v_m < v < v_c : \ \alpha = p \ ; \ \beta = (p-1)/2 \]
\[ v > v_c : \ \alpha = p \ ; \ \beta = p/2 \]
\[ \alpha = 2\beta + 1 \]
\[ \alpha = 2\beta \]

With allowance for smooth transition between breaks,

Fits most afterglow data remarkably well
Predicted in the Standard Model, but seen rarely:

* Reverse shock  $\Rightarrow$ prompt emission  \(\text{(Sari and Piran 1999)}\)
  
  optical: GRB 990123  \(\text{(Akerlof et al 1999)}\)
  radio : 990123, 991216, 000926, 980329  

* Inverse Compton emission
  
  000926  \(\text{(Harrison et al 2001)}\)
  980329  \(\text{(Yost et al 2002)}\)
  \(\varepsilon_e / \varepsilon_B \geq 1 ; \ n_0 \ \text{relatively high}\)

Non–standard behaviour observed:

* Re–brightening
  
  970508, 000301c, 980326, 000911(?)
  > Additional, late energy source
  > Density jump in ambient medium
  > Microlensing
  > Supernova (e.g. 980425/SN1998bw; 011121/SN2001ke)

* Hard electron energy spectrum
  
  000301c, 010222......

* Slow post–jet–break radio decline  \(\text{(Frail et al 2002)}\)
Possible cause for re–brightening:

- Second episode of energy injection (Panaitescu, Meszaros & Rees ’98, Zhang & Meszaros ’02, Zhang & Meszaros ’01)
- Continuous energy source
- Spherical+Jet fireballs
- Inhomogeneous ambient medium (Ramirez–Ruiz et al ’01, Dai & Lu ’02)

980326, 000911: Supernova ?
000301c : microlensing ?
\( \nu_{\text{opt}} > \nu_c; \quad p \approx 2; \) microlensing model
Upper panels: $p > 2$; In lower panels $p < 2$ yield better fit

$p \approx 1.5$ in GRB 010222  
(Sagar et al 2001, Cowsik et al 2001,
Bhattacharya 2001, Panaitescu & Kumar 2001)

Upper cutoff in energy distribution is important in determining light curve and spectrum
Standard Afterglow Theory

\[ n(\gamma_e) \, d\gamma_e \propto \gamma_e^{-p} \, d\gamma_e ; \quad p > 2 ; \quad \gamma_m < \gamma_e < \gamma_u \]

No. of electrons = \[ \int_{\gamma_m}^{\gamma_u} n(\gamma_e) \, d\gamma_e \]

Energy content in electrons = \[ \int_{\gamma_m}^{\gamma_u} \gamma_e n(\gamma_e) \, d\gamma_e \]

In both integrals, the lower limit dominates; \( \gamma_u \) is ignored

\[ F_\nu (t) \propto \nu^{-\beta} t^{-\alpha} ; \quad \alpha (p), \beta (p) \]

Extension to \( p < 2 \):

* Energy content dominated by upper cutoff \( \gamma_u \)

* Evolution depends on \( \gamma_u(t) \):
  both \( \gamma_m \) and \( \gamma_u \) important

* Cooling break \( \gamma_c << \gamma_u \) \Rightarrow electrons are always "Fast Cooling",
  even if \( \nu_c > \nu_m \)

* Pile–up at \( \gamma_c \)

**DB 2001:** Assume \( \gamma_u \propto \Gamma_{\text{Shock}}^q \)

\[ => \alpha = \alpha (p,q) ; \text{reduces to } p > 2 \text{ expressions for } q = 1 \]

But if \( \alpha_1, \alpha_2 \) are decay indices before and after jet break,

\[ 3\alpha_2/4 - \alpha_1 = \begin{cases} 
  \frac{3}{4} & \nu < \nu_c \\
  \frac{1}{2} & \nu > \nu_c 
\end{cases} \]

independent of \( p, q \) –if both are constant
Illustration of a "bump" in energy distribution of electrons at the synchrotron cooling energy if $p < 2$
Light curves for $p = 1.5$:  
upper panel: below cooling frequency  
lower panel: above cooling frequency  
The break in the light curve corresponds to the "jet break"
$\alpha_1 \approx 0.7 \ ; \ \alpha_2 \approx 1.4 \quad \Rightarrow \quad \nu > \nu_c \ at \ optical \ bands$

$\beta_{opt-x} \approx 0.7 \quad \Rightarrow \quad p \approx 1.4 \ , \ q \approx 1$

Panaitescu and Kumar (2001) find similar result: $p \approx 1.5$ for GRB 010222

For several other GRBs, they find $p < 2$, but need the "injection break" corresponding to $\gamma_u$ to be present within the observed frequency range. Injected electron energy spectrum steepens to $p > 2$ above $\gamma_u$
Diffusive Shock Acceleration theory predicts $p = (r + 2)/(r - 1)$, where $r = v_{\text{up}} / v_{\text{down}}$ is the "compression ratio". For strong non–relativistic shocks $r \to 4$, and $p \to 2$. In relativistic shocks, $r \to 3$ and $p \to 2.5$ (Blandford and Ostriker 1978; see following talk by J.G. Kirk for a detailed discussion of shock acceleration).

Shell SNRs exhibit $p$ mostly above 2.0, but plerions, in which the electron energy distribution may have been established due to the encounter of the relativistic pulsar wind with nebular material in a standing shock, have values of $p$ distinctly less than 2.0. This is at variance with the prediction of the simple Diffusive Shock Acceleration theory.
\( \alpha_{\text{radio}} \) vs \( \alpha_{\text{optical}} \) after jet break. Both are expected to be equal to \( p/2 \) in the standard model (dotted line). Determination of \( \alpha_{\text{radio}} \) and \( \alpha_{\text{optical}} \) are not simultaneous, as one has to wait for \( \nu_m \) to fall below the radio frequency.

- Non–relativistic transition?
- Mag. field stratification? \( (\text{e.g. Rossi and Rees 2002}) \)
- Additional electron population?
- \( \varepsilon_e / \varepsilon_B \) time dependent?