Long-term Accretion Rate Modulation by an External Accretion Disk in GRBs

From R. Sari: Pre-Swift Picture:

Lightcurve Breaks
Simultaneous at all frequencies

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

- \( v > v_m \) \( F_v \propto t^{-p} \sim t^{-2.2} \) \( \Delta \alpha \approx -1.1 \) optical, x
- \( v_a < v < v_m \) \( F_v \propto t^{-1/3} \) \( \Delta \alpha = -5/6 \) IR, mm
- \( v < v_a \) \( F_v \propto t^0 \) \( \Delta \alpha = -1/2 \) low radio

The break is substantial at all frequencies.
Procedure to Estimate Energy

- Estimate $K$ corrected $E_{iso}$

- Estimate break time $t_{jet}$

- Use $\theta_{jet} = 0.06 \left( \frac{t_{jet}}{1+z} \right)^{3/8} \left( \frac{E_{iso}}{n} \right)^{1/8}$ (SPH)

- $E_\gamma = E_{iso} \left( \theta_{jet} \right)^2 / 2$

We fixed $n = 0.1$
GRBs – Standard Candles !?

From R. Sari:

\[ 4\pi D^2 F = E_{iso}(\gamma) \]

Luminosity distribution is spread over a factor of 500

\[ 2\pi \theta^2 D^2 F = E_\gamma \]

Frail et. al.

After correcting for beaming, spread <10
Frail et al. (2001)

Jet Break Times and Energetics

<table>
<thead>
<tr>
<th>GRB</th>
<th>$F_\gamma$</th>
<th>z</th>
<th>$d_L$</th>
<th>$E_{iso}(\gamma)$</th>
<th>$t_j$</th>
<th>$\theta_j$</th>
<th>$E_\gamma$</th>
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<th>Method</th>
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(1) 970508: optical (25d)
(1) 970508: X-ray (25d) (off-scale)
(1) 970508: radio (25d)
(2) 970828: optical (2.2d)
(2) 970828: X-ray (2.2d)
(2) 970828: radio (2.2d)
(3) 980703: optical (7.5d)
(3) 980703: X-ray (7.5d)

GRB 980703A Light Curve

<table>
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<tr>
<th>Flux (erg/cm²/s)</th>
<th>Burst Time (days)</th>
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<td>3.0E-13</td>
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LEGEND: ● - keV

(off-scale)
(3) 980703: radio (7.5d)
(4) 990123: optical (2.04d)

GRB 990123A Light Curve

LEGEND: B V R r I i J K none
(4) 990123: X-ray (2.04d)

GRB 990123A Light Curve

Flux (erg/cm²/s)

Burst Time (days)

LEGEND: • 2-10 keV  ■ 1.6-10 keV
(4) 990123: radio (2.04d)
(5) 990510: optical (1.2d)
(6) 990705: optical (1d)
(7) 991216: optical (1.2d)
(7) 991216: X-ray (1.2d)

GRB 991216A Light Curve

Legend: ● 2-10 keV
(7) 991216: radio (1.2d)
(8) 000301C: optical (5.5d)
(8) 000301C: radio (5.5d)
(9) 000418: optical (25d)
(9) 000418: radio (25d)
(10) 000926: optical (1.45d)
(10) 000926: X-ray (1.45d)

LEGEND: • 1.6-10 keV
(10) 000926: radio (1.45d)
Summary:

Pre-Swift Evidence for beaming
Weak to non-existent
Racusin et al. (2008), Nature, 455, 183
GRB 060206 and the quandary of achromatic breaks

Curran et al. (2007) - GRB 060206
“Swift XRT and Optical Jet Break Candidates”

Liang et al. (2008): “It is fair to conclude that we still have not found a textbook version of a jet break after many years of intense observational campaigns.”
Zhang et al. (2006)
Q: Is the long-term decay in the light curve from GRBs due to the deceleration of a jet, or to a decrease in the rate of fuel supply onto the central engine that powers the jet?
Accretion Disks: often found in binary systems
Lynden-Bell & Pringle (1974)
C, Lee, & Goodman (1990)
Time Dependent Accretion Disk Evolution:

By combining the equations for mass continuity and angular momentum, one obtains a diffusion equation for the surface density:

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r} \left[ r^{1/2} \frac{\partial}{\partial r} \left( \nu \Sigma r^{1/2} \right) \right]$$

where $\Sigma$ is the surface density (mass/area) and $\nu$ is the viscosity coefficient (area/time).
Standard Model: Time Dependent Solution:

\[ \nu = C r \Sigma^{2/3} \]

\[ C = \alpha^{4/3} \left( \frac{k_B}{\mu m_p} \right)^{4/3} \left( \frac{\kappa_{es}}{12acG M_{BH}} \right)^{1/3} \]

\[ \frac{\Sigma(r, t)}{\Sigma_0} = \left( \frac{t}{t_0} \right)^{-15/16} f \left[ \left( \frac{r}{r_0} \right) \left( \frac{t}{t_0} \right)^{-3/8} \right] \]

where

\[ f(u) = (28)^{-3/2} u^{-3/5} \left( 1 - u^{7/5} \right)^{3/2} \]

\[ M_d(t) = (28)^{-3/2} \frac{4\pi}{7} r_0^2 \Sigma_0 \left( \frac{t}{t_0} \right)^{-3/16} \]

Spreading of outer disk edge:

\[ \left( \frac{r}{r_0} \right) = \left( \frac{t}{t_0} \right)^{3/8}. \]
Scenario:

I. Fall-back Disk: ~ -3 which is too steep for standard model dynamical return of material following hypernova (Kumar, Narayan, & Johnson 2008ab)

II. Transient Plateau: Period of viscous adjustment of the small amount of gas starting from progenitor envelope into disk. (could also be fall-back of progenitor core: Kumar et al.)

III. Standard Disk Self-similar Decay: ~ -1.2 (Zhang et al.), & ~ -19/16 ~ -1.2 (& -4/3 advective disks)
Implications:

- If true, then can’t apply Sari et al formalism to infer beaming angle and hence beaming-corrected energy

\[ t_0 \approx 5 \times 10^4 \text{s} r_{0,11}^{7/3} \alpha_{-1}^{-4/3} M_{d, -4.5}^{-2/3} m_{BH, 1}^{1/3} \]

- Gives a rough scaling for the transient plateau interval, i.e., the II/III transition.

- Would be different for progenitor (Kumar et al.)
Progenitor Fall-Back versus accretion disk at late times:

-From Kumar et al. 2008b:

\[
\frac{r}{(10^{10} \text{ cm})} \sim 1.5 \left(\frac{t}{100 \text{ s}}\right)^{2/3} \left(\frac{M_{\text{BH}}}{10 M_{\text{sun}}}\right)^{1/3}
\]

-If the late-time accretion were only due to progenitor fall-back, for GRBs such as 060729, one would need \( r > 3 \times 10^{13} \text{ cm} \) for progenitor.
Looking at the Big Picture:

-Maybe in some small fraction of GRBs the progenitor is completely obliterated, so that late time accretion is not possible, while for the majority, late time accretion via an external disk powers the late time lc.