GRB
in the Swift Era
and beyond

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GRB: *basic numbers*

- Rate: $\sim 1$/day inside a Hubble radius
- Distance: $0.1 \leq z \leq 6.3$ ! $\rightarrow D \sim 10^{28}$ cm
- Fluence: $F = \int \text{flux} \cdot dt \sim 10^{-4} - 10^{-7}$ erg/cm$^2$ $\sim 1$ ph/cm$^2$ (g-rays !)
- Energy output: $10^{53} (\Omega/4\pi) D^{2.28.5} F^{-5}$ erg
  but, jet: $(\Omega_j/4\pi) \sim 10^{-2} \rightarrow E_{\gamma,\text{tot}} \sim 10^{51}$ erg
  $\rightarrow E_{\gamma,\text{tot}} \sim L_\Theta \times 10^{10}$ year $\sim L_{\text{gal}} \times 1$ year
- Rate[GRB ($\gamma$-obs)] $\sim 10^{-6}(2\pi/\Omega)$ /yr/gal $\rightarrow 1$/day ($z \leq 3$)
  but Rate [GRB (uncollimated)] $\sim 10^{-4}$ /yr/gal,
  while Rate [SN (core collapse)] $\sim 10^{-2}$/yr/gal, or $10^7$/yr $\sim 1$/s ($z < 3$)
GRB: standard paradigm

Hyperaccreting Black Holes

NS - NS merger

0.01 $M_\odot$ torus

very, very fast jet

BH - NS merger

0.1 $M_\odot$ torus

BH - WD merger

1 $M_\odot$ torus

few $M_\odot$ torus

NS/BH - He core merger after common envelope

collapsar = rotating, collapsing "failed" supernova

Bimodal distribution of $t_\gamma$ duration

$\leftarrow \downarrow$ Short

($t_\gamma < 2$ s)

$\rightarrow \uparrow$ Long

($t_\gamma > 2$ s)


Mészáros grb-gen06
BH + accr. Torus $\rightarrow$ Jet

- Both collapsar or merger $\rightarrow$ BH+accr.torus$\rightarrow$fireball
- Massive rot. *: sideways pressure confines/channel outflow $\rightarrow$ **fireball Jet**
- Nuclear density hot torus $\rightarrow$ can have $nn\rightarrow e^\pm$ jet
- Hot infall $\rightarrow$ convective dynamo $\rightarrow$ $B\sim 10^{15}$ G, twisted (thread BH?)
  $\rightarrow$ **Alfvénic or $e^\pm\gamma$ jet**
- (Note: magnetar might do similar)
Explosion $\rightarrow$ FIREBALL

- $E_\gamma \sim 10^{51} \Omega^{-2} D^2_{28.5} F^{-5} \text{ erg}$
- $R_0 \sim c t_0 \sim 10^7 t_{-3} \text{ cm}$
  
  $\rightarrow$ Huge energy in very small volume

- $\tau_{\gamma\gamma} \sim (E_\gamma/R_0^3 m_e c^2) \sigma_T R_0 \gg 1$

  $\rightarrow$ Fireball: $e^\pm, \gamma, p$ relativistic gas

- $L_\gamma/E_\gamma/t_0 \gg L_{Edd} \rightarrow$ expanding ($v \sim c$) fireball

  (Cavallo & Rees, 1978 MN 183:359)

- Observe $E_\gamma > 10 \text{ GeV}$ …but

  $\gamma\gamma \rightarrow e^\pm$, degrade 10 GeV $\rightarrow 0.5 \text{ MeV}$?

  $E_\gamma E_t > 2(m_e c^2)^2/(1-\cos \Theta) \sim 4(m_e c^2)^2/\Theta^2$

  $\rightarrow$ Ultrarelativistic flow $\rightarrow \Gamma \geq \Theta^{-1} \sim 10^2$

  (Fenimore et al. 93; Baring & Harding 94)
Relativistic Outflows

- Energy-impulse tensor: \( T_{ik} = w \, u_i u_k + p \, g_{ik} \),
  \( u^i \): 4-velocity, \( g_{ik} \)= metric, \( g_{11}=g_{22}=g_{33}=-g_{00}=1 \), others 0;
  ultra-rel. enthalpy: \( w = 4p \propto n^{4/3} \); \( w, p, n \): in comoving-frame

- 1-D motion: \( u^i=(\gamma,u,0,0) \), where \( u = \Gamma \, (v/c) \),
  \( v \): 3-velocity, \( A \)= outflow channel cross section:

- Impulse flux, energy flux, particle number flux:
  - \( Q=(w \, u^2 + p) \, A \)
  - \( L= wu \, \Gamma \, c \, A \)
  - \( J= n \, u \, A \)

- Isentropic flow: \( L, \, J \) constant \( \rightarrow \)
  \( w \, \Gamma /n = \text{constant} \) (relativistic Bernoulli equation);
  for ultra-rel. equ. of state \( p \propto w \propto n^{4/3} \), and cross section \( A \propto r^2 \)
  \( \rightarrow n \propto 1 / r^2 \, \Gamma \) comoving density drops
  \( \rightarrow \Gamma \propto r \) “bulk” Lorentz factor initially grows with \( r \).

- But, eventually saturates, \( \Gamma \rightarrow E_j/M_jc^2 \sim \text{constant} \)
Shock formation

• Collisionless shocks (rarefied gas)
• “Internal” shock waves: where?
  If two gas shells ejected with $\Delta \Gamma = \Gamma_1 - \Gamma_2 \sim \Gamma$, starting at time intervals $\Delta t \sim t_v$, they collide at $r_{is}$,

$$r_{is} \sim 2c \Delta t \Gamma^2 \sim 2c t_v \Gamma^2 \sim 10^{12} t_3 \Gamma_2^2 \text{ cm}$$

(internal shock)

[Alternative picture: magnetic dissipation, reconnection]

• “External shock”: merged ejected shells coast out to $r_{es}$, where they have swept up enough external matter to slow down, $E = (4p/3) r_{es}^3 n_{ext} m_p c^2 \Gamma^2$,

$$r_{es} \sim \left( \frac{3E}{4pn_{ext} m_p c^2} \right)^{1/3} \Gamma^{-2/3} \sim 3.1 \times 10^{16} \left( \frac{E_{51}}{n_0} \right)^{1/3} \Gamma_2^{-2/3} \text{ cm}$$

(external shock)
Fireball Model: long GRBs

E.g., recent review on *GRB-Swift results & implications*:
Internal & External Shocks in optically thin medium:

**LONG-TERM BEHAVIOR**

- **Internal** shocks (or other, e.g. magnetic dissipation) at radius $r_i \sim 10^{12}$ cm
  \[ \rightarrow \gamma\text{-rays (burst, } t_\gamma \sim \text{sec)} \]
- **External** shocks at $r_e \sim 10^{16}$ cm; progressively decelerate, get **weaker and redder** in time (Rees & Meszaros 92)
- Decreasing Doppler boost: \[ \rightarrow \text{roughly, expect radio } @ \sim 1 \text{ week }, \text{optical } @ \sim 1 \text{ day} \] (Paczynski, & Rhoads 93, Katz 94)

**PREDICTION**:

- Full quantitative theory of:
  - External **forward** shock spectrum **softens** in time: X-ray, optical, radio … \[ \rightarrow \text{long fading afterglow} \]
    (t \sim \text{min, hr, day, month})
  - External **reverse** shock (less relativistic, cooler, denser):

  **Prompt Optical** \[ \rightarrow \text{quick fading} \]
  (t \sim \text{mins})

Standard External Forw. & Rev. Shock Synchrotron & IC spectrum

Lower energy: Synchrotron (reverse: eV, forward: MeV)

Higher energy: Inv. Compton (forward: GeV)
Shock Photon Spectrum

- **Non-thermal power law** spectrum, both in int. and ext. shocks, due to
- **Synchrotron**, peak at ~200 keV (or ~ eV?)
- **Inv. Compton**, peak ~ GeV (or ~200 keV ?)
- Sy peak location, ratio Sy/IC dep. on $B_{sh}$, $\gamma_e$, $\Gamma$
- Peak **softens** with time
- Ratio Sy/IC **decr** w. time

\[ E^2N_E \]

\[ F_E \]

\[ E \]

\[ t \]

\[ R \]

\[ O \]

\[ X, g \]

Mészáros grb-gen06
GRB 970228: BeppoSAX
Discovery of an afterglow

- X-ray location: 2-3 arcmin → raster
- → optical (arcsec) & radio location
- Can identify host galaxy, redshift located at cosmological dist.

Feb 28
F_x \sim 3 \times 10^{-12} \text{ erg cm}^{-2} \text{ keV s}^{-1}, \text{ decr. By 1/20}

(Marzao et al 1997, Nature 387:783)
GRB afterglow blast wave model

- Simplest case: adiabatic forward shock synchrotron rad’n from shock-accel. non-thermal e-
- $F(\nu, t) \propto \nu^{-\beta} t^{-\alpha}$
- $\alpha = (3/2) \beta$
- Parameters $E_0, \varepsilon_e, \varepsilon_B$, $(\beta=(p-1)/2)$

GRB 970228 as blast wave:

Wijers, Rees & Mészáros 97 MNRAS 288:L51 fit to

**Snapshot Afterglow Fits**

- **Simplest case:** $t_{\text{cool}}(\gamma_m) > t_{\text{exp}}$, where $N(\gamma) \propto \gamma^{-p}$ for $\gamma > \gamma_m$ (i.e. $\gamma_{c(ool)} > \gamma_m$)

- **3 breaks:** $v_{a(bs)}$, $v_m$, $v_c$

- $F_v \propto v^2 (v^{5/2})$ ; $v < v_a$ ; $\propto v^{1/3}$ ; $v_a < v < v_m$ ; $\propto v^{-(p-1)/2}$ ; $v_m < v < v_c$ ; $\propto v^{-p/2}$ ; $v > v_c$

(Mészáros, Rees & Wijers '98 ApJ 499:301)

Break frequency decreases in time (at rate dep. on whether ext medium homog. or wind (e.g. $n \propto r^{-2}$))

Collapsar & SN: a direct link - but always?

- Core collapse of star w. $M_t \sim 30 \, M_{\odot}$
  → BH + disk (if fast rot.core)
  → jet (MHD? baryonic? high $\Gamma$, + SNR envelope eject (?))
- 3D hydro simulations (Newtonian SR) show that baryonic jet w. high $G$ can be formed/escape
- SNR: not seen \textit{numerically} yet
  \textbf{but:} several suggestive observations, e.g. late l.c. hump + reddening; and ..
- \textit{Direct} observational (spectroscopic) detections of GRB/ccSN

Collapsar & SN ANIMATION
Credit: Derek Fox & NASA
Collapsar & ccSN:

GRB 030329 - SN 2003dh & others

- 2nd Nearest “unequivocal” cosmological GRB: \( z=0.17 \)
- GRB-SN association: “strong”
- Fluence: \( \text{10}^{-4} \text{ erg cm}^{-2} \), among highest in BATSE, but \( t_{\gamma} \approx 30 \text{s} \), nearby; \( E_{\gamma,\text{iso}} \approx \text{10}^{50.5} \text{erg} \):
  - ~typical,
- \( E_{\text{SN2003dh,iso}} \approx \text{10}^{52.3} \text{erg} \)
  - \( \approx E_{\text{SN1998bw,iso}} \) (\( \llgrb980425 \))
  - \( v_{\text{SN,ej}} \approx 0.1c \) (\( \rightarrow \) “hypernova”)
- GRB-SN simultaneous? at most: < 2 days off-set (from opt. lightcurve)
  - \( \rightarrow \) i.e. not a “supra-nova”)
- But: might be 2-stage (<2 day delay) *- NS-BH collapse ?
  - \( \rightarrow \) ν predictions may test this!
- Some others:
  - GRB 031203/SN2003lw;
  - GRB 060218/SN2006aj; ...
Light curve break: Jet Edge Effects

- Monochromatic break in light curve time power law behavior
- expect $\Gamma \propto t^{-3/8}$, as long as $\theta_{\text{light cone}} \sim \Gamma^{-1} < \theta_{\text{jet}}$, (spherical approx is valid)
- “see” jet edge at $\Gamma \sim \theta_{\text{jet}}^{-1}$
- Before edge, $F_v \propto (r/\Gamma)^2 I_v$
- After edge, $F_v \propto (r \theta_{\text{jet}})^2 I_v$, $\rightarrow F_v$ steeper by $\Gamma^2 \propto t^{-3/4}$
- After edge, also side exp.
$\rightarrow$ further steepen $F_v \propto t^p$

Mészáros, L’Aqu05
GRB 030329:

- evidence for SN
- evidence for refreshed shock and
- evidence for 2-comp. jet:
  \[ \theta_\gamma \sim 5^\circ \]
  \[ < \theta_{\text{radio}} \sim 17^\circ \]

Berger et al 03, Nature 426, 154

More recently (Swift): several XR light-curve breaks, but: conflicting evidence for (a?)chromatic breaks
Jet Collimation & Energetics

\[ E_\gamma = E(\Gamma > 100) \]

\[ E_{K,x-ray} = E(\Gamma > 10) \]

\[ E_{rel} = E_\gamma + E_{K,rad} = E(\Gamma > \text{few}) \]

Berger et al. 03

Frail et al. 01

- ↑Jet opening angle inv. corr. w. \( L_\gamma^{(iso)} \)
- ← \( L_{\gamma^{(corr)}} \sim \text{const.} \)
- Mean collim. “correction” \(<(4\pi/2\Delta \Omega_j)> \sim 10^{-2} \)
- GRB030329: 2-comp. jet?
  \( \vartheta_g \sim 5^\circ < \vartheta_{\text{radio}} \sim 17^\circ \)
- → \( E_{\text{total}} = E_\gamma + E_{\text{kin}} \sim \text{const.} \)

( → quasi-standard candle)
$E_{pk} \text{ vs } E_{\gamma \text{tot}}$

Better correl. than $E_{pk} \text{ vs } E_{\gamma \text{iso}}$ (?)

Ghirlanda, Ghisellini, Lazatti, aph/0405602
(see also Friedman & Bloom, aph/0408413) $E_{pk} \propto E_{\gamma}^{0.7}$

os, L’Aqu05
z-measures?

- Variability $V$ vs. $E_{\gamma,iso}$ (Fenimore, Ramirez-Ruiz, Reichart..)
- Lag vs. $E_{\gamma,iso}$ (Norris, Bonnell,..)
- Hardness ($E_{pk}$) vs. $E_{\gamma,iso}$ (Amati et al, Bagoly et al, Schmidt..)
- $E_{pk}$ vs. $E_{\gamma,jet}$ (Ghirlanda et al 04)
- $E_{pk}$ vs. $E_{iso}$ vs. $t_{\text{break}}$ (Liang & Zhang 05)
- $E_{pk}$ vs $E_{iso}$ vs. $t_{0.45}$ (Firmani et al, 06; where $t_{0.45} \sim V$)

Mészáros, L’Aqu05
Reasons for Amati - Ghirlanda?

- E.g, internal shocks, \( E_p \sim E_{sy} \sim \Gamma B' \gamma_e^2 \sim \Gamma B' \sim B \sim U^{1/2} \)
  \( \sim (L/r^2)^{1/2} \sim L^{1/2} t_v^{-1} \Gamma^{-2} \) (Zhang, Mészáros 02 ApJ 581, 1236)

  (since \( r \sim c t_v \Gamma^2 \) - but, \( t_v \), \( \Gamma \) ~ const. for diff. \( L \)?)

- E.g photospheric characteristic temperature,
  \( E_p \sim \Gamma T' \sim \Gamma (L/\Gamma^2 r_{ph}^2)^{1/4} \sim \Gamma^2 L^{-1/4} \) (since \( r_{ph} \sim L/\Gamma^3 \) )
  if use Frail : \( L \sim \theta^{-2} \), and causality : \( \Gamma \sim \theta^{-1} \)
  \[ \rightarrow E_p \sim L^{3/4} \] (Rees, Mészáros 05 ApJ 628, 847)

- If photosphere is at known radius of WR *,
  \( E_p \sim \Gamma T' \sim \Gamma (L/\Gamma^2 R_*^2)^{1/4} \sim \Gamma^{1/2} L^{1/4} \)
  bulk of fluid moves at \( \Gamma \sim 3^{-1/2} \theta^{-1} \) since outside that KH mix
  \[ \rightarrow E_p \sim L^{1/2} \] (Thompson astroph/0507387; Thompson, Meszaros & Rees, aph/0608....)
Optical Flash : GRB 990123

(Akerlof et al. 1999; Meszaros & Rees 1997; Sari & Piran 1999; Kobayashi 2000)
Prompt Optical Flashes

- **GRB 990123** → bright (9\textsuperscript{th} mag)
  prompt opt. transient (Akerlof et al 99)
  – 1st 10 min: decay steeper than forw. shock
- Interpreted as reverse external shock
  (pred : Mészáros&Rees ’97)
- **99-02: Great Desert:**
  Lack of flashes, upper limits $m_v \sim 12-15$
- **but:** New generation robotic tels:
  ROTSE III, Super-LOTIS, RAPTOR, KAIT, TAROT, NEAT, Faulkes, REM; etc
- → more prompt optical flashes, e.g.:
  GRB 021004, 021211;
  and new “semi- prompt” flashes:
  GRB 030418, 30723 : ≠ GRB 990123 !
  → $t > 211, 50 \text{s}$ resp, see forw. shock only?
- and now... **Swift era:**
  GRB 041219A (Raptor; Vestrand 05);
  GRB 050319 (Raptor; Wozniak et al 05)
  GRB 050401 (Rotse III, Quimby et al 05)
  GRB 050801 (Rotse III, Rykoff et al 05)
  GRB 050904 (TAROT, Gendre et al, 06)
  GRB 060206 (Raptor, Wozniak et al, 06)

Mészáros, L’Aqu05
Cosmology with GRBs?

High-z GRB distance measures

- Positive K-correction:
  \[ \text{flux} \sim \text{constant at } z \geq 3 \]

- Optical/UV: Ly \( \alpha \) cutoff \( \rightarrow \) redshift out to \( z < 5 \) for Swift
- Forward shock exp. fluxes

\[ \text{O/IR} \quad \text{Lamb, Reichart 00} \]

\[ \text{Ciardi & Loeb 00} \]
IR & XR hi-z detectability

XR detectability

O/IR ZX detectability

**SWIFT**

**Three instruments**
Gamma-ray, X-ray and optical/UV

**Slew time:** 20-70 s!

>95% of triggers yield XRT det
>50% triggers yield UVOT det.

**BAT:** Energy Range: 15-150 keV
FoV: 2.0 sr
Burst Detection Rate: 100 bursts/yr

**XRT:** Energy Range: 0.2-10 keV

**UVOT:** Wavelength Range: 170-650 nm

Launched Nov 04

Mészáros, L’Aqu05
SWIFT: New Results

- > 140 new afterglows localized since launch
- Redshifts for >40 long GRB and 4 short GRB
- \(<z_{\text{long}}\) ~2.4-2.8, which is 2x Beppo-Sax distance
  (i.e. significantly fainter & redder, than Beppo-Sax afterglows!)
- \(<z_{\text{short}}\) ~0.1-0.7; \(L_{\text{short}} \sim 10^{-2} L_{\text{long}}\); compact merger
- XR light curves (10^2s-10^4s): new features
  (both long and short) - steep + shallow decay, flares
  → evidence for continued activity?
  In the period \(1 \text{ min} < t < \text{ hrs}\),
  new features show up, which
  may be natural extensions of the standard burst & AG model (or ..?)
SWIFT: New Results, cont.

- Short bursts localized, hosts identified, redshifts measured
- VHZ (very high redshift) bursts: several >5, one 6.29
- Prompt optical/IR flashes (one very bright)
- GRB/SN, at least two spectroscopic, more ...
New features seen by Swift: A Generic X-ray Lightcurve

BUT: not all features in all bursts
Afterglow: when does it start?

- Standard interpretation: AG starts at
  \[ t_{\text{dec}} \sim \frac{3}{4} \left( \frac{r_{\text{dec}}}{2} \right) c \Gamma^2 (1+z) \]
  \[ \sim \frac{3}{8} c \Gamma^2 \left( 3E/4\pi n m_p c^2 \Gamma^2 \right)^{1/3} (1+z) \]
  \[ \sim 10^2 \left( \frac{E_{52}}{n_0} \right)^{1/3} \Gamma_2^{-8/3} (1+z) \text{ s} \]

- But, for prompt duration \( T = T_\gamma = T_{\text{outflow}} \sim T_{90} \)
  - “Thin shell”: \( T < t_{\text{dec}} \rightarrow \) AG start at \( t_{\text{dec}} \) above
  - “Thick shell”: \( T > t_{\text{dec}} \rightarrow \) AG start at \( T \sim T_\gamma \sim T_{90} \)
Example: GRB 050315

Vaughn et al. 2005
Initial steep drop:
\[ F_x \propto (t-t_0)^{-\alpha} \]

- Current bet: **tail end of GRB** *(high latitude emission)*:
  radiation from outside main beam, \( \theta > \Gamma^{-1} \)
  - arrives at \( t \sim R\theta^2/2c \) later than from \( \theta \sim 0 \),
  - is softer by \( D \sim t^1 \) *(Nousek et al 05, Zhang et al 05, Panaitescu et al 05)*

- expect \( \alpha = 2+\beta \), where \( F \sim t^{\alpha}\nu^\beta \) *(Kumar, Panaitescu 00)*
  - OK, generally; departures may be understood

- **Possible alternatives:**
  - Photopion rapid cooling --> drop (Dermer, 06, aph/...
Initial rapid decay:

High latitude emission

Radiation Components:

1: Prompt $\gamma$-rays (GRB) from l.o.s. angles $\theta < \Gamma^{-1}$

2: tail-end of GRB, from high latitude emission: $\gamma$-rays emitted promptly, but from angles $\theta > \Gamma^{-1}$; arrive at time $t \sim R\theta^2/2c$ later than from $\theta \sim 0$, and is softer by $D \sim t^{-1}$; expect $\alpha = 2 + \beta$, ~ OK

3: afterglow, from forward shock at l.o.s. angles $\theta < \Gamma^{-1}$; later than (or partially overlap with) high latitude comp. (2)
High latitude issues...

• Time slope $\alpha$ depends on choice of $t_0$
  $\to$ can fit $t_0$ such that slope is satisfied
  i.e., determine $t_{\text{dec}}$? (Liang et al astroph/0602142)

• When $T > t_{\text{dec}}$ (and also when $T < t_{\text{dec}}$) can have an admixture of
  (a) afterglow (l.o.s) $\theta < \Gamma^{-1}$, and (b) high latitude $\theta > \Gamma^{-1}$ components.
  Generally $\beta_{\text{prompt}} < \beta_{\text{steep}}$, so can accommodate steeper decays
  than $2 + \beta_{\text{prompt}}$ (O'Brien et al, 05)

• Flares: $t_0$ fit can give pulse ejection time by engine (Liang et al 06)

• Structured jet: for on-beam viewing jet shape has little effect, but
  off-beam can get shallower slope (Dyks et al aph/0511699)

• From initial steep decay slope, $t_0$ constraints suggest $t_0 \sim t_{\text{trigger}}$
  may infer prompt emission radius $R_\gamma$ (Lazzati, Begelman aph/0511658)
Retrofit:
The $t_0$ which fits the steep decay slope generally agrees with the onset of the rising segment of the last peak before the decay

Liang, et al aph/0602142
Shallow decay

- Slope $0.3 \leq \alpha \leq 1$:
  likely due to “refreshed shock” …
  I.e. the forward afterglow shock receives continued
  reinforcement from late-arriving ejecta

**NOTE**: late *arriving*, but not necessarily late *ejected!*

(Rees-Meszaros 98, Panaitescu, PM, MJR 98, Kumar-Piran 00, Sari-Meszaros 00,
Nousek et al 05, Zhang et al 05, Granot-Kumar 05)
Shallow decay 
\[0.2 \leq \alpha \leq 1\]

- Probably due to **refreshed shocks**, due *either* to:
  - **Long** duration ejection 
    \[t \sim t_{\text{flat}}\] ; **or**
  - **Short** duration ejection 
    \[t \sim t_{\gamma}\], but with range of \(\Gamma\), 
    e.g. \(M(\Gamma) \sim \Gamma^{-s}\), \(E(\Gamma) \sim \Gamma^{-s+1}\), 
    for \(\rho \sim r^{-g}\) ext. medium:

\[
\alpha = \frac{-4-4s+g+sg+\beta(24-7g+sg)}{2(7+s-2g)}
\]


*Note*: Fit to Swift data \(\Rightarrow\) \(\Gamma\) distrib. may be a broken power law

(Granot, Kumar astro-ph/0511049)
Refreshed (shallow decay)

- Note: \( E_{\text{Xshallow}} \leq E_{\gamma \text{prompt}} \) [O’Brien, et al, 06].

  But in order for refreshed shock to dominate the afterglow, energy input in refreshed component needs exceed that in prompt

  \[ \Rightarrow \text{either - rad’n. effic. } \varepsilon_{\gamma} > \varepsilon_{x} \quad (\text{eg prompt is Poynting dominated ?..}) \]

  \( \text{or} \) - fraction of refreshed shock energy undetected (IR? GeV?…)

  \( \text{or} \) - preactivity evacuates cavity, or

  fraction of energy into electrons \( \propto t^{1/2} \) (Ioka et al, astro-ph/0511749)

- Alternative: shallow decay due to emission from anisotropic jet lines of sight just outside sharp edge of main bright jet (Eichler-Granot astroph/0509857)

- Other possibilities:

  - \( E_{\text{kin}} \) underestimated (also in BATSE), so \( \varepsilon_{\gamma} \) is reasonable relative to \( \varepsilon_{x} \)

Giant X-ray Flare: GRB050502b

GRB Fluence: 8E-7 ergs/cm²

Flare Fluence: 9E-7 ergs/cm²

XR Flares

• Main puzzles: - large energy \( E_{xfl} \leq 0.1-1 E_{\gamma \text{prompt}} \)
  - steep rise/decay \( F \propto (t-t_0)^\alpha, \alpha \sim \pm 3-6 \)

• Possible causes:
  - refreshed (forward) shocks (rise & decay too shallow)
  - reverse IC component (one shot affair- where is forward?)
  - interaction with external matter (rise/decay slope?)
  - continued central engine activity, e.g.
    internal shocks, dissipation (difficult for central engine, but address temp. slope, total energy - less problematic than others?)
XR Flare triggers?

• Gravitational instability $\rightarrow$ disk fragmentation
  $\rightarrow$ lumpy accretion
  (Perna, Armitage, B.Zhang)

• MHD accretion- magnetic tension ("springy")
  $\rightarrow$ lumpy accretion
  (Proga & Begelman, Fan, Proga & B.Zhang)

• Short bursts: BH-NS disr (SPH GR numerical)
  $\rightarrow$ prompt accretion + extended tail
  $\rightarrow$ delayed lumpy accretion
  (Davies, et al 05; Lee et al 00, Rosswog et al 04; Laguna, Rasio 05)
MHD accretion? (Proga & Begelman 03)

Accretion rate

\[ \frac{\dot{m}_e}{M_3} \]

\( \text{time} \)
Main Possible Explanations of long GRB afterglow new features

- **Initial drop:** likely due to tail end of GRB (high latitude emission): rad’n from $\theta > \Gamma^{-1}$ arrives at $t \sim R\theta^2/2c$ later than from $\theta \sim 0$, is softer by $D \sim t^{-1}$; expect $\alpha = 2 + \beta$, ~ OK

- **Shallow decay:** probably “refreshed shocks”, *either* from Longer ejection ($t \sim t_{\text{flat}}$); *or* Short ejection ($t \sim t_{\gamma}$), but with range of $\Gamma$, e.g. $M(\Gamma) \sim \Gamma^{-s}$, $E(\Gamma) \sim \Gamma^{-s+1}$

- **Flares:** likely due to continued central engine activity: main constraints: very sharp rise and decline ($t^{\pm 3} \leftrightarrow t^{\pm 6}$)

- **But:** remains work in progress- depending also on new observations
Short & Long Afterglows

• Big question: are they the same?
  • 0th order answer: looks like yes
    - initial steep decay ✓
    - XR flares ✓
    - “normal forward shock” decay ✓
    - jet break ✓
  • But: 1st order differences are interesting
    - Avg. kin. energy/solid angle x100 smaller
    - Avg. jet angle x2 larger than in long bursts

(Fox et al 05, Panaitescu 05)
Short Bursts

- **Hosts**: E, Irr, SFR
  (compat. W. NS merg, ✓
  but: some SGR, other?)
- **Redshift**: < 0.1 to ~ 0.7
- **XR, OT, RT**: yes (mostly)
- **XR l.c.**: similar to long bursts?
  (XR bumps too- late engine?)
SHB afterglow fits

- So far, > 11 shb afterglows, 5-6 hosts (D. Fox talk, Nature 05)
- AG fits for **050709** (Irr), **050724** (E) (Panaitescu, aph/0511588)

Using fluxes and break times, standard ag model:

\[
\begin{align*}
\Gamma &= 6.5 \left( \frac{E_{50}}{n_0} \right)^{1/8} t_d^{-3/8}, \quad \theta_j = \Gamma(t_b)^{-1} \\
\theta_j &= 9^\circ \left( \frac{n_0}{E_{50}} \right)^{1/8} t_{bd}^{3/8}, \\
E_j &= \pi \theta_j^2 E \sim 10^{49} n_0^{1/4} \left( \frac{E_{50}}{t_{bd}} \right)^{3/4} \text{ erg}
\end{align*}
\]

High / low dens. soln's:
- **050709**: \( \theta_j > 6^\circ \), \( 10^{-4} < n < 10^{-1} \text{ cm}^{-3} \), \( E \sim 3-300 \times 10^{50} \text{ erg/s} \)
- \( \theta_j > 2^\circ \), \( n < 10^{-5} \text{ cm}^{-3} \), \( E \sim 2-10 \times 10^{49} \text{ erg/sr} \)

- **050724**: \( \theta_j > 8^\circ \), \( 10^{-1} < n < 10^3 \text{ cm}^{-3} \), \( E \sim 1-50 \times 10^{49} \text{ erg/sr} \)

- **but**: GRB **050724** (Grupe et al, 06, in prep.) Chandra late obs.: no break seen.

- **while**: GRB **051221A**: Swift + 2 Chandra obs.: well defined jet break appears @ 4 days \( \Rightarrow \) \( \theta_j \sim 7^\circ \), \( E_j \sim 2 \times 10^{49} \text{ erg} \)
Short burst paradigm: **NS-NS** or **NS-BH**

merger \[\Downarrow\]

BH + accretion

- Paradigm seems compatible with hosts, and (for Kerr BH-NS) some simulations suggest extended activity & flares \[\Rightarrow\]

simulation

Laguna, Rasio 06; (Preliminary)

Mészáros grb-gen06
BH-NS merger?
(Laguna & Rasio ‘06)

Schwarz.BH-NS

Kerr-proBH-NS
50
Prompt optical afterglows

- ⦿ expected behavior: reverse shock causes prompt (10’s of sec) bright ($m_V \geq 9$) optical flash, decaying much faster than long-lasting forward shock optical afterglow (Mészáros-Rees 97)
- First seen in GRB 990123 ⦿ Rotse (Akerlof et al. 99), and few other bursts, but rare: why?
- Could be that
  - rev. shock hi-mag → suppress?
  - pair formation → spec. to IR?
  - rev. shock rel. → spec. to UV?
- Latest: GRB 050904 (z=6.29) shows prompt bright opt flash!
Most distant

long burst from

Swift ( z=6.29 )::

GRB050904

- Discovered/localized by Swift BAT, XRT, UVOT
- Prompt ground I,R band TAROT, P60 upper limits,
- Detection J=17 mag FUN/SOAR, VLT → photometric z >6
- Spectroscopy Subaru 8.5 m @ t=3.5 day: z = 6.29 !
GRB 050904 as an XR beacon

- At a redshift $z=6.29$ (~reionization; most distant known QSR: $z \sim 6.4$)
- GRB 050904 X-ray flux exceeded that of the brightest known X-ray QSO SDSS J0130+0524, by up to $10^5$, for days

SDSS J0130 (multiplied by 100)

• Prompt O/UV flash as bright as 990123 (~ 9th mag!) at same z (rev. shock..)
• $E_{iso} \sim 10^{54}$ erg, similarly very high ; decay similarly steep (~ $t^{-3}$)
• Observed at 800-1000 nm by TAROT (25 cm tel.!) [Boer et al, astro-ph/0510381]
Why 050904 and 990123?

- Need high $E_{\text{iso}} \sim 10^{54}$ erg? (or small beam?)
- If reverse shock rest frame spectrum in UV (relativistic reverse shock?)
  $\rightarrow$ ground detection @ O/IR: need high $z$
  (or else need enough rest-frame spectrum extending redwards of Ly$\alpha$, so not absorbed)
- Need burst with strong flares (weak “smooth” afterglow component)?
- Other non-obs. or weak flash: pair formation, or weak field in ejecta $\rightarrow$ rest-frame spectrum shifted to IR?
Origin of prompt Opt-flash

- 4 prompt optical flashes have been measured while the gamma-rays were still in progress
- in some (GRB 050904, Boer et al, astro-ph/0510381; also GRB 041219a, Vestrand et al, astroph/0503521)
  - prompt optical l.c. correlates with gamma-rays
    ⇒ emission from the same region? (e.g. internal shock?)
- in others (GRB 050401, Rykoff et al astroph/0508495, GRB 990123, Akerlof et al 00)
  - prompt optical l.c. does NOT correlate with gamma-rays
    ⇒ emission from different region? (e.g. reverse shock?)
Different prompt gamma/opt correlations?

Vestrand et al, 06, aph/0503521
GRB 060218 / SN 2006aj


• Long(est) BAT T90 = 2100 s duration
• XRT after 100 s, rising to max at ~1000s, followed by steep decay, then PL decay
• UVOT brightening to UV plateau @ 30ks and later O plateau @ 40ks, decay to minimum @200ks, rebrightening @700ks
• XR non-thermal plus increasing BB component which dominates before the steep decay @1000s (kT_{BB} ~ 0.17 keV)
Interpreted as shock break-out of an anisotropic, semi-relativistic component from an optically thick progenitor stellar wind (Campana et al. 06; Note: Fan–Piran alternate model: their objections apply to spherical single component, whereas here assumed 2+ components, anisotropic semirelativistic + spher. envelope)
Conclusions

• Swift is significantly expanding our view & understanding of afterglows
• New early XR, O features appear to be understandable within context of standard afterglow model, with (not quite mastered) extensions
  Understanding of new XR “smooth” features is reasonable, but fluid dynamics remains controversial - and MHD may play a large role.
• XR flares are significant challenge, also for progenitor, central engine
• Relation of early XRT, UVOT to BAT flux levels pose challenges to prompt GRB gamma-ray mechanisms (efficiencies, etc..)
• Commonality & differences between short and long GRB afterglow features will yield important clues, need much further work
  (diff. due to lower $E_{\text{iso}}$, broader $\theta_{\text{jet}}$, E vs. Irr, Sp hosts?)
  Information on long and short GRB jet breaks (collimation) not very extensive yet, possibly due to higher avg. $z$ and lower fluxes?
• O/UV late afterglows largely support forward shock AG interpretation
• Prompt O/IR flash detection may hold vital clues (rareness? reverse shock interpretation? other..?)
• Potential for high-$z$ IGM probing, SFR mapping appears poised for transition from wish to actual data to be modeled $\rightarrow$ cosmology.